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A Modified Constant-Stress Coupon for Enhanced Natural Crack Start during Fatigue Testing

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ABSTRACT

This report details the development of a modified constant-stress coupon for use in fatigue testing. This novel coupon design has a significantly greater surface area along the notch boundary that is subjected to the peak stress, and it is useful in studies of the probabilistic growth of in-service fatigue cracks where fatigue life is governed by the most severe defect. The extended region of uniform stress is achieved by shape optimisation of the notch boundary, resulting in the elimination of the highly-localised stress concentration that is a characteristic feature of a traditional dog-bone coupon. The presence of an extensive region of uniform stress increases the incidence of fatigue cracking from small naturally-occurring surface imperfections or discontinuities, as well as more uniformly distributing the fatigue cracking over the region of constant stress. Stress intensity factors have also been computed for simulated crack growth trajectories for edge cracks starting at various locations distributed along the notch boundary. Use of the constant-stress coupon reduces the number of coupons that need to be tested in order to attain desired statistical confidence levels, leading to significant time savings and greatly reduced costs in conducting fatigue testing programs studying the initiation and growth behaviour of small cracks.

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Executive Summary

The Structural and Damage Mechanics Group in the Airframe Technology and Safety Branch of Aerospace Division has been deeply involved in research to develop and apply structural and damage mechanics methods and technologies to enhance the safety, availability, and reduce the cost of ownership of airframes in service with the Royal Australian Air Force. Included amongst its wide range of capabilities are a unique and novel shape optimisation technology for the repair and fatigue life enhancement of airframe components, advanced computational and analytical tools and methods for improved determination of fatigue and crack growth life of airframes, and integrated analytical and numerical modelling of both complete and local structures for the improved assessment of structural response and capability.

This report details the development of a modified constant-stress coupon for use in fatigue testing. A constant-stress coupon is a novel design that has a significantly greater surface area along the notch boundary that is subjected to the peak stress. This extensive region of uniform stress is achieved by shape optimisation of the boundary of the notch, resulting in the elimination of the highly-localised stress concentration that is a characteristic feature of a traditional dog-bone fatigue testing coupon. The shape optimisation method that has been used here is based on the advanced and powerful shape optimisation technique that has been pioneered by the Structural and Damage Mechanics Group, and which has recently been modified and ported to be used with the Abaqus finite element analysis software code.

As the constant-stress fatigue coupon design is being used in studies involving crack growth, an assessment of its performance from a fracture mechanics perspective was also conducted. This involved the detailed computation of crack-growth trajectories and stress intensity factors for through-thickness edge cracks emanating from points distributed along the shape-optimised notch boundary. An advanced two-dimensional boundary element analysis technique was used for these calculations. The results reported here will serve to permit comparison with the crack paths that occur during the fatigue testing of the coupons.

The use of constant-stress fatigue coupons will significantly assist research into improving the fundamental understanding of the probabilistic growth of in-service fatigue cracks where the fatigue life is governed by the most severe defect. The presence of an extensive region of uniform stress will increase the incidence of fatigue cracking from small naturally-occurring surface imperfections or discontinuities, as well as potentially more uniformly distributing the fatigue cracking over the region of uniform stress. Use of the constant-stress coupon will reduce the number of coupons that need to be tested in order to attain desired statistical confidence levels, leading to significant time savings and greatly reduced costs in conducting fatigue testing programs to study the initiation and growth behaviour of small cracks. The outcomes of this research into fatigue cracking will be applied to the long-term structural integrity management of both ageing and new ADF airframes.

Authors

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Aerospace Division

Mr Witold Waldman completed a BEng (with distinction) in Aeronautical Engineering at the Royal Melbourne Institute of Technology in 1981. He commenced work in Structures Division in 1982, at what was then the Aeronautical Research Laboratory. He has published a number of papers and reports, and his experience has focussed on stress analysis using finite element and boundary element methods, structural mechanics, fracture mechanics, computational unsteady aerodynamics, structural dynamics testing, digital filtering of flight test data, nonlinear optimisation, and spectral analysis. His recent work has been in the areas of structural shape optimisation and the computation of stress intensity factors. He is currently a Senior Research Engineer in the Structural and Damage Mechanics Group in the Airframe Technology and Safety Branch of Aerospace Division within the Defence Science and Technology Group.

Robert Kaye
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Mr Robert Kaye joined what was then the Structures Division of the Aeronautical Research Laboratory in 1990 as a structural engineer with a background in full-scale testing. The first three years at DSTO were spent in evaluation of bonded repairs primarily using finite element methods. Included in that was the analysis of repairs to fuselage skin lap-joints, wing skin planks and bulkhead frames. More recently, he has been involved with structural and mechanical aspects of full-scale fatigue test installations. In particular, he played a key role in the development of a low-stiffness air-spring for the application of static load to a vibrating airframe. This work was followed by a period of several years doing research and development into the alleviation of stress concentrations by way of adaptive shape optimisation. This has been applied to concave metallic free boundaries and to the adhesive layer and end tapering of boron patches bonded to metallic structure. Upon his retirement, he is now a DST Honorary Fellow in Aerospace Division.

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Dr Xiaobo Yu completed a BEng in Naval Architecture Engineering in 1988, and a MEng in Structural Mechanics in 1991, both from Shanghai Jiao Tong University; and a PhD in Civil Engineering from the University of Sydney. He has held a lecturing position in Shanghai Jiao Tong University and several senior research positions in the University of Sydney and the University of NSW, and was also attached to Pacific Engineering Systems International as a CRC-ACS Visiting Research Fellow. In 2007 he joined what was then the Defence Science and Technology Organisation, and he is currently Science Team Leader for Structural Mechanics in Aerospace Division. In the context of airframe safety and life assessment and life extension, his main interests and responsibilities include structural shape optimisation, computational structural analysis and multi-axial fatigue.

Contents

Nomenclature

a	crack length
E	Young's modulus of the material
F	boundary correction factor (beta factor)
K	stress intensity factor
K_t	net-section stress concentration factor
K_{tg}	gross-section stress concentration factor
S	local tangential stress at notch surface
S_∞	remote uniaxial tension stress
x	x-coordinate
y	y-coordinate
σ	stress along notch boundary
σ_{max}	maximum tangential stress
υ	Poisson's ratio of the material

1. Introduction

Prior work in DST Group by McDonald (1999a) has involved the computation of stress concentration factors (SCFs) for various fatigue test coupon profiles composed of straight lines and circular arcs. These coupons were required for use in fatigue testing to aid in the fatigue life management of RAAF airframes. To help maximise test machine usage efficiency and to provide the necessary statistical data for accurate estimation of fatigue life, it was desirable to test many short cracks on a single specimen. To achieve this, a test coupon was required that had a notch with a relatively large surface area of uniform stress (where the stress is constant within a specified small range). This led McDonald (1999b) to establish the design of an aluminium coupon that maximised the length of uniform stress under uniaxial tensile loading.

Following on from the work of Mattheck et al. (1992), the Structural and Damage Mechanics Group within DST Group has successfully developed and employed shape optimisation technology for the reduction of peak stresses occurring at typical stress concentrations such as fillets and holes (Heller, Kaye and Rose 1999; Waldman, Heller and Chen 2001; Burchill and Heller 2004; Heller et al. 2009, Waldman 2015). In essence, the method relies on adding material where stresses are high and removing material where stresses are low. Waldman and Heller (2006, 2015) have also significantly extended this in-house shape optimisation capability in order to be able to address problems that involve the simultaneous reduction of multiple stress peaks. The implementation of the method for use with the MSC Nastran finite element analysis (FEA) code that was developed by Braemar (2005) has also recently been ported by Kaye and Waldman (2016) to make use of the Abaqus FEA code running on a Linux–based computer system.

A distinct characteristic of shape-optimal designs is the presence of one or more large regions of uniform stress along the stress concentrator boundary, where the stress is constant within a small tolerance. Hence, in DST Group, Westcott (2010) and Kaye (2010) have previously taken advantage of this feature by applying shape optimisation methods to design specialised fatigue test coupons that have extensive regions of uniform stress. These shape-optimised coupon geometries are characterised by having the desired extensive regions of nearly-constant stress along a large proportion of the notch boundary, with the peak stress in the coupon corresponding to the stress level that is associated with the region of uniform stress.

The advantage offered by a constant-stress fatigue coupon is that there is a much larger area along the notch surface that is subjected to the peak stress, as the highly-localised stress concentration produced by a traditional dog-bone coupon is eliminated. It is therefore anticipated that the incidence of fatigue cracking from small naturally-occurring surface imperfections or discontinuities will be duly increased, as well as potentially being more uniformly distributed over the region of constant stress. This can serve to reduce the number of coupons that need to be tested, resulting in significant time savings and greatly reduced costs in conducting fatigue testing programs. The desired outcome from such

fatigue tests is to improve the fundamental understanding of the probabilistic growth of fatigue cracks from small naturally-occurring defects, where the in-service fatigue life of the component is assumed to be governed by the most severe defect that is present (Cetin, Härkegård and Naess 2013). In addition, Molent, Barter and Wanhill (2011) and Barter, Molent and Wanhill (2012) have noted that surface imperfections and discontinuities are features that are inherent to the material and the manner of production of the component, and that the existence of such defects in typical aircraft alloys leads to fatigue cracking in tests of both coupons and components.

As a result of the novel properties offered by a constant-stress fatigue test coupon, such designs have recently begun to be extensively utilised by the Aircraft Forensic and Metallic Technologies Group within DST Group (Shekhter et al. 2015; Loader, Shekhter and Turk 2015; Loader et al. 2016; Niclis and Harrison 2016; Shekhter et al. 2016; Turk 2016a; Turk 2016b; Turk and Niclis 2016). Prior to this, in conducting their fatigue test program on multiple coupons that have a low SCF (low-K_t), Yu et al. (2014) have noted that, over a region of low stress concentration, the lead crack that dictates the fatigue life is often the fastest growing crack that starts from one of the worst discontinuities. They referred to this phenomenon as "natural crack start", which cannot be reproduced using traditional dog-bone coupons such as those defined in ASTM (2012), because the stress concentration that is inherent in the design of those coupons is significant enough to dictate the starting positions of the fatigue cracks. Yu et al. (2014) have also noted a further limitation, in that, by confining the crack starting locations to the area of higher stress, fewer initial discontinuities and local material properties are sampled, which affects the growth of small cracks. As a result, the largest crack that eventually results in failure may start from a less severe discontinuity or grow at a slower rate. Also, when the largest crack starts from a location that is next to, but not exactly at, the peak stress location, the use of nominal peak stress overestimates the actual fatigue driving force. Consequently, Yu et al. (2014) have concluded that the fatigue test results obtained from traditional types of dog-bone coupons will exhibit more scatter in total fatigue life, and any distribution of life data would be skewed to a longer life, when compared to those on an actual aircraft structure.

The effectiveness of the prior optimal coupon design has been confirmed by Yu et al. (2014) through experimental strain measurement as well as fatigue tests under spectrum loading. However, as designed, these coupons have on occasion experienced undesirable premature failures in the grip region during other subsequent test programs. These failures typically occurred while undertaking testing at low load levels, with commensurately long specimen fatigue lives. A significant factor contributing to these failures is considered to be the use of oversized test specimen grips, which affect the gripping action. This is thought to produce fretting damage, which then leads to instances of fatigue failure in the region where the coupon is being clamped by the grips. Therefore, it became apparent that a need exists for the design of a Modified Constant-Stress Coupon with a view to reducing the incidence of coupon failures originating in the grip area. The performance of the coupon whose design is reported on herein is expected to be better because of the increased width of the new coupon in the grip area. It must also be kept in

mind that the previous fatigue testing work undertaken with the narrower specimen has already produced an extensive usable body of results. In order to maintain compatibility with those results, it is desirable that the length of the constant-stress region in the modified coupon be very similar to that of the original design. This Report documents the design of this new Modified Constant-Stress Coupon.

In order to provide some background that serves as a basis for comparison, Section 2 gives the results of analyses of a variety of typical non-optimal non-constant stress dog-bone coupon designs. One of those designs has in fact previously been used in a coupon fatigue testing program in the DST Group. Section 3 then goes on to provide the results of a stress analysis of the original constant-stress coupon design. The design of the new Modified Constant-Stress Coupon is then described in Section 4. The results of a detailed fracture mechanics analysis of potential cracking along the notch boundary of the new coupon are presented in Section 5, and it includes simulated crack-growth trajectories and associated stress intensity factors for through-thickness edge cracks of various lengths. Finally, the conclusion is presented in Section 6.

2. Stress analysis of typical dog-bone coupons with non-optimal notch profiles

It is considered useful to develop a better quantitative understanding of the stress distribution in the notch region of some typical dog-bone axial fatigue test coupon geometries. For this purpose, a number of two-dimensional ¼-symmetry boundary element models of coupon designs are created here and analysed using the FADD2D boundary element code (Chang and Mear 1995; Newman et al. 2006). The assumed linear-elastic material properties for these aluminium coupons are a Young's Modulus of E = 72.4 GPa and a Poisson's ratio of υ = 0.33. Each model is subjected to a uniform uniaxial tensile load of 100 MPa applied to the ends of the specimen, and this was deemed to be capable of providing stress results in the notch region (the area of interest) comparable to those that would be expected if the actual grip loading could be more accurately simulated. Plane stress conditions were assumed in the analysis, which was deemed to be reasonable as the thickness of these coupons is small relative to the other dimensions.

2.1 Notch with large 100-mm constant-radius arcs

In prior DST Group work reported much earlier by McDonald (1999a), a simple notch design was developed that utilised a circular arc of large constant radius to produce a notch profile. The purpose behind this design was to try to minimise the stress concentration effect associated with the notch. This type of notch design is shown in Figure 1, and the hatched areas represent the grip length of 40 mm that had been adopted. The coupon dimensions for this notch design were: notch radius = 100 mm, total coupon

length = 160 mm, width = 40 mm, thickness = 6.35 mm, notch half-length = 38 mm, notch depth = 7.5 mm, and net section half-width = 12.5 mm.

A FADD2D ¼-symmetry model was created and analysed using the previously specified linear elastic material properties for aluminium (see Appendix A for a listing of the input deck, which is also located in Objective folder fAV1044714). The FADD2D-computed normalised stress response along the notch boundary, σ/σ_{max}, is shown in Figure 2. Here σ is the tangential stress, and σ_{max} is the maximum tangential stress. The net-section SCF is K_t = 1.081 for this design, which compares very well with K_t = 1.082 obtained from a 3D analysis using the StressCheck finite element code (McDonald 1999a). The gross-section SCF is K_{tg} = 1.730. The stress response obtained here consists of a broad peak, centred on x = 0 mm. These results show that the stress changes by 8% over approximately 30 mm of the notch length (–15 mm ≤ x ≤ +15 mm), and by 33% over approximately 60 mm of the notch length (–30 mm ≤ x ≤ +30 mm). Hence, it is evident that the constant-radius specimen design cannot meet the requirement of having a significant region with uniform stress.

2.2 Notch with constant central width and large constant 100-mm radius fillets

An alternative dog-bone coupon notch design that is composed of a long constant-width centre section with transitioning fillets of large constant 100-mm radius is shown in Figure 3. This dog-bone coupon geometry was selected on the basis that it is similar to those that are used in many fatigue testing programs, often with circular through-thickness holes added to the centre section. The geometry shown in Figure 3 is expected to result in a considerable constant-stress zone in the central constant-width region. However, it is also anticipated that a significant stress concentration will occur in the fillet regions.

A ¼-symmetry 2D model of the geometry shown in Figure 3 was created and analysed using the FADD2D boundary element program (see Appendix B for a listing of the input deck, which is also located in Objective folder fAV1044714). The previously specified linear elastic material properties for aluminium were used, and the applied load once again consisted of a uniform uniaxial tensile load of 100 MPa. The computed normalised stress response along the notch boundary, σ/σ_{max}, is shown in Figure 4. The net-section SCF for this coupon design is K_t = 1.071, while the gross-section SCF is K_{tg} = 1.714. It is noted that the stress response has a broad peak, located at about x = ±23.9 mm. The stress is quite constant over approximately 30 mm of the notch length in the central region of the coupon (–15 mm ≤ x ≤ +15 mm), albeit at a value of about σ/σ_{max} = 0.93, which is 7% lower than the peak stress. The left and right peaks (from symmetry) in the stress distribution along the notch boundary occupy about 40 mm of the total notch length (–35 mm ≤ x ≤ –15 mm and +15 mm ≤ x ≤ +35 mm). Although this design has a considerable zone of constant stress in its central region, the presence of the significant peak in the stress distribution would be expected to result in crack growth in that particular area during fatigue testing, rather than in the zone of constant stress.

2.3 Notch with constant central width and moderate constant 30-mm radius fillets

Another dog-bone coupon notch design, this time composed of a constant-width centre section with transitioning fillets of moderate constant 30-mm radius, is shown in Figure 5. These fillets have a much smaller radius than the 100-mm radius fillets used in the previous section and, as a result, they are expected to produce a more severe stress concentration effect.

A FADD2D ¼-symmetry 2D model of this geometry was created and analysed using the previously specified linear elastic material properties for aluminium (see Appendix C for a listing of the input deck, which is also located in Objective folder fAV1044714). The applied load once again consisted of a uniform uniaxial pressure of 100 MPa. The computed normalised stress response along the notch boundary, σ/σ_{max}, is shown in Figure 6. The net-section SCF for this design is $K_t = 1.240$, while the gross-section SCF is $K_{tg} = 1.984$. These values are considerably more severe than those obtained when the 100-mm radius fillets were used. The stress response has a broad peak, located at about $x = \pm 23.5$ mm. The stress is quite constant over approximately 30 mm of the notch length in the central region of the coupon (-15 mm $\leq x \leq +15$ mm), albeit at a value of about $\sigma/\sigma_{max} = 0.80$, which is 20% lower than the peak stress. The left and right peaks (from symmetry) in the stress distribution occupy about 40 mm of the total notch length (-31 mm $\leq x \leq -15$ mm and $+15$ mm $\leq x \leq +31$ mm). Although this design has a considerable zone of constant stress in its central region, the presence of the significant peak in the stress distribution would be expected to result in crack growth originating somewhere in that particular area during fatigue testing, rather than in the zone of constant stress.

3. Prior optimal constant-stress notch profile

Some years ago now, the original DST Group shape optimisation code was ported to work with the MSC Patran and Nastran finite element analysis software, and the specifics of this version of the code are covered by Braemar (2005). The process used for preparing an optimal shape for manufacture is described by Wescott and Heller (2009). Taken in combination, these procedures were used by Wescott, Jones and Heller (2010) and then Kaye (2010) to design the original constant-stress fatigue test coupon.

The first constant-stress specimen was designed by Wescott, Jones and Heller (2010) using 2D shape optimisation techniques, as the then implementation of the code was not working correctly for 3D open boundary problems. Their specimen was 6.35 mm thick and had a nominal grip area of 40×40 mm at each end. The grip load was modelled as a constant traction (tangential pressure) during the optimisation process, and was implemented using nodal forces. A short 5 mm buffer zone between the grip line and the end of the notched section was included. As the specimen is 160 mm in total length, this

results in a notch length of 70 mm. The minimum section width was 24 mm at the centre of the specimen, corresponding to a notch depth of 8 mm. Minimum radius of curvature constraints in the range 5 mm to 25 mm were investigated, and a value of 20 mm was chosen for the production version of this design. The net-section K_t was 1.03 and the length of notch profile with up to 2% stress variation was 50 mm.

After correcting a bug in the code, Kaye (2010) subsequently ran a 3D version of the shape optimisation algorithm, which for the unsmoothed optimal notch shape produced a net-section K_t of 1.03. This specimen, which is shown in Figure 7, differed slightly from the earlier one, in that the depth of the notch was 7.5 mm rather than 8 mm. The total arc length of the constant-stress region along each notch is about 55.5 mm, falling within the region –27.5 mm ≤ x ≤ +27.5 mm. The uniformity of the stress in the constant-stress zone was found to be very good, to within a small fraction of one per cent.

As mentioned by Kaye (2010), the 5 mm buffer zone between the grip region and the end of the notch was chosen because a discontinuity occurs at the edge of the grip. The exact stress/strain state at this location is unknown, as it depends on the amount of surface yielding and/or slip that occurs over the grip area contact surface. Preliminary finite element analyses conducted by Wescott, Jones and Heller (2010) had also shown that excessive local stresses occur near the ends of the notch if a suitable buffer zone is not included.

A FADD2D ¼-symmetry 2D model of the Kaye (2010) coupon was created and analysed using the previously specified linear elastic material properties for aluminium. An initial FADD2D input deck was created using a custom-written Fortran 90 program called CreateDogboneCouponModel (see Appendix D for the source code listing of this program, and Appendix E for the associated input deck, both of which are also located in Objective folder fAV1044714). Note that the coordinates of the notch profile that were used here were those that had been obtained after the radius-of-curvature coordinate-smoothing process described by Wescott and Heller (2009) had been applied. The applied load once again consisted of a uniform uniaxial pressure of 100 MPa. The initial input deck was manually edited to convert it from a full model to the desired ¼-symmetry model.

The computed normalised stress response, σ/σ_{max}, along the smoothed notch boundary is shown in Figure 8. The net-section SCF for this design is K_t = 1.038, which is in good agreement with the prior result of K_t = 1.030 that was reported by Kaye (2010), and the gross-section SCF is K_{tg} = 1.660. The normalised stress is quite constant over an arc length of approximately 54.4 mm along the notch in the central region of the coupon (–27.0 mm ≤ x ≤ +27.0 mm). Although the stress response is very flat, the stress level in this region is about 0.7% lower than the peak stress, which occurs at about x = 25.5 mm. This is likely to be a consequence of a number of interacting factors. Firstly, the smoothing process, which has been applied to produce the smoothed notch boundary, has a small detrimental impact on the uniformity of the boundary stresses, as originally noted by Kaye (2010) and subsequently further investigated by Evans, Yu and Heller (2015). Secondly, first-order

elements were used in the original Nastran-based shape optimisation, whereas the FADD2D code utilises 2nd-order boundary elements that are capable of more accurately resolving local stress variations associated with any given geometry. Finally, the optimal shape is based on a 3D finite element analysis, whereas the FADD2D analysis is 2D in nature.

4. Design of the modified coupon with optimal constant-stress notch profile

The prior constant-stress coupon design has experienced undesirable failures in the grip area during the fatigue test program, and a contributing factor is considered to be the use of oversized grips. By increasing the width of the coupon in the grip area, while maintaining the minimum width in the central region, it is expected that failures in the grip area will be avoided. As the previous fatigue testing work has already produced a quantity of results, it is required to create a new coupon design that maintains as much compatibility with those results as possible. In that respect, it is desired that the length of the constant-stress region in the modified coupon be very similar to that of the original design.

The previous MSC Patran/Nastran–based DST Group shape optimisation procedure has recently been modified for use with the Abaqus finite element analysis code by Kaye and Waldman (2016). This new version of the shape optimisation code was used here for designing the new Modified Constant-Stress Coupon. The Abaqus-based procedures are presently capable of performing a 2.5D optimisation analysis. This means that the *y*-displacement through the thickness of the model is maintained at each point on the notch profile while the profile is being optimised.

4.1 Nominal geometry and material properties

The nominal design of the Modified Constant-Stress Coupon is shown in Figure 9, and it is based on the previous design for a constant-stress coupon reported in Kaye (2010). As before, the new coupon is 6.35 mm thick, and has linear-elastic material properties typical of an aluminium alloy: E = 72.4 GPa and υ = 0.33. To improve the performance in the grip area, the gross width of the new coupon has been increased to 60 mm, with a gripped area that is now 60 mm × 60 mm at each end. The new design also includes a 25-mm buffer zone between the grip line and the end of the notched region, whereas it was 5 mm in the previous design described by Kaye (2010). The increased size of this buffer zone is expected to make the stresses less sensitive to different boundary conditions that might be utilised to simulate the grip loading. The total length of the new coupon is 244 mm. The minimum cross-sectional width in the notched region is the same as before (25 mm). As the notch depth in this Modified Constant-Stress Coupon is more severe than previously, the length of the notch region was increased from 70 mm to 74 mm. This will ostensibly

provide additional room over which the constant stress zone can develop, thus offsetting to some degree the effects of the more severe stress concentration geometry.

4.2 Initial finite element mesh

In order to perform the shape optimisation, it is necessary to create an initial finite element model. A ⅛-symmetry model of the coupon was developed in order to reduce computation time and to avoid potential numerical errors. The model was created using the MSC Patran pre- and post-processing software, and then an Abaqus input deck was written out. Figure 10 shows a general view of the 3D finite element mesh that was created. The model utilised six layers of 8-noded hexagonal elements through the half-thickness.

A side view of the finite element model with the optimisation zone highlighted is shown in Figure 11. The assumed starting shape of the notch is a straight line, which was subdivided into 80 segments of equal length. The grip load was modelled as a uniformly-distributed constant traction force, and it was implemented using nodal forces. For this linear-elastic model, the applied uniaxial traction load was equivalent to a force of 50.02 kN (calculated by summing up the individual contributions of the forces applied at the nodes). This leads to a gross-section average stress of 131.3 MPa, and a net-section average stress of 315.1 MPa.

As we will be performing a linear elastic stress analysis, the load level can be scaled to obtain suitable stress levels in the notch zone to suit the particular requirements of the fatigue test.

4.3 Performing the shape optimisation

Prior to performing the shape optimisation, some further processing of the initial Abaqus input deck was conducted in accordance with the method described by Kaye and Waldman (2016) in order to prepare it for use by the shape optimisation code. The entire notch region was chosen as the movable boundary during the optimisation process (see Figure 11). The nodal movement at each point along the notch boundary was calculated using the maximum through-thickness stress. A minimum radius of curvature constraint of 20 mm was applied. All seven nodes through the thickness at each location on the notch boundary were moved by the same amount at each iterative step. The optimisation process was allowed to proceed for 400 iterations, whereupon it was manually terminated.

4.4 Raw results of shape optimisation

The resulting raw shape for the optimised constant-stress coupon that was produced by the shape optimisation process is shown in Figure 12. The contours of maximum principal stress from the finite element analysis are shown in Figure 13. The distribution of normalised principal stress, σ/σ_{max}, along the notch boundary is shown in Figure 14, where σ is the largest principal stress through the thickness at each location, and σ_{max} is the

maximum value of the principal stress along the optimised notch boundary. The peak occurs at the centre of the notch boundary, and is σ_{max} = 330.3 MPa. Using this value of stress, the gross-section SCF is K_{tg} = 2.516 for this configuration, while the net-section SCF is K_t = 1.048.

Referring to Figure 14, it is noted that, as expected, the normalised maximum principal stress in the central region of the optimised notch boundary is very uniform. This constant-stress zone extends over an arc length of approximately 51.2 mm, falling within the region –25.3 mm ≤ x ≤ +25.3 mm. The standard deviation of the normalised principal stress in the constant-stress region is only 0.006%, which is negligible, indicating the optimality of the solution. The arc length of the present constant-stress region is 7.7% less than that of the original constant-stress coupon.

In Figure 15, the maximum principal stress contour levels were adjusted to lie between a maximum of 330.3 MPa and a minimum of 310.5 MPa, with 12 contour bands in between. Each of these contour levels represents a 0.5% change in stress relative to the peak stress, for a total range of 6.0%. To provide some details of a higher resolution, Figure 16 shows contours of maximum principal stress that lie within 1.0% of the peak value.

As depicted in Figures 13–16, the distribution of the principal stress is very uniform along a large section of the notch surface of the optimised boundary contour, just as required. Furthermore, the variation of the maximum principal stress in the thickness direction is generally very low, this being particularly so at the centre of the coupon. Through-thickness variation in the maximum principal stress only becomes noticeable near the end of the constant stress zone. As expected, the through-the-thickness stress distribution peaks at the mid-plane of the coupon.

4.5 Preparation of raw optimal shape for manufacture

As described by Wescott and Heller (2009), and more recently by Evans, Yu and Heller (2015), past experience with the numerically-controlled machining of free-form notch shapes has indicated that it is desirable to process the notch coordinates so that the shape of the notch can be represented by a series of many short circular arcs. This conversion procedure also incorporates the facility for performing some smoothing of the raw notch shape in order to reduce the variability of the radius of curvature (ROC) along the notch boundary. In practice, the shape transformation process produces only very minor adjustments to the raw shape, and the resulting shape is still essentially free-form. In addition, the ROC-smoothing process has a very small effect on the stress distribution along the notch profile, which although noticeable is often negligible. Experience with some optimal shapes appears to indicate that the ROC-smoothing process can result in stresses that increase slightly near the end of the zone of constant stress (see Figure 8 for an example of this type of behaviour).

A plot of the ROC distribution computed from the nodal coordinates along the entire (mirrored) raw unsmoothed as-optimised notch boundary is shown in Figure 17. The ROC at any given node was computed by a fitting circular arc through the three sets of coordinates comprised of that node and its immediate left and right neighbours (except at the start and end nodes along the boundary). The effect of the ROC constraint of 20 mm is clearly visible at the two ends of the notch boundary. From the response displayed in Figure 17, it is apparent that there are significant fluctuations in the ROC, with a large number of very high ROC values being present. These large fluctuations in ROC value have been found to cause difficulties during the manufacturing of optimal shapes using standard computer numerically-controlled machining techniques.

The rapid and high-amplitude oscillations in the radius-of-curvature of the as-optimised geometry are potentially caused by the use of first-order elements during the iterative finite element analysis. Prior shape optimisation using second-order elements did not appear to display this rather unsatisfactory behaviour. Further investigation is warranted in order to remediate this problem. It is considered that it would be better not to apply the previously-developed automated smoothing procedures in a brute force manner. It would be preferable to determine the cause of the radius-of-curvature problems and address them directly.

Upon subsequent closer investigation here, these rapid and high-amplitude oscillations in the computed ROC values have been identified as being associated with very small transitions in slope between the edges of some of the linear 8-noded hexahedral first-order finite elements. These cause the large calculated ROC values associated with pairs of elements whose connected edges are nearly collinear. This behaviour is depicted in Figure 18, where the shape of the raw optimal profile near x = 0 mm has been plotted (solid line). The presence of these “flat” areas, with their commensurately-high ROC values (based on a 3-point circular arc curve fit), is clearly evident in the plot of the raw unsmoothed optimal profile. It is believed that these “flat” regions are caused by the numerical approximations inherent in the use of first-order finite elements to obtain the optimal solution, as prior shape optimisation solutions obtained using second-order finite elements did not display the type of oscillatory ROC behaviour found here (see Waldman, Heller and Chen 2001; Waldman and Heller 2006; Waldman and Heller 2015). The dashed line shows the results of fitting a smooth curve through every second point of the original data set, resulting in a smooth line that accurately follows the underlying shape of the optimal profile.

Hence, as in the prior work performed by Kaye (2010), it is necessary here to undertake ROC smoothing of the raw geometric coordinates of the optimised boundary shape in order to make the notch suitable for manufacturing. Based on an assessment of the relevant information presented in Figure 17 and Figure 18, it was decided to accomplish this smoothing by using a two-phase process in order to produce a result of sufficiently high quality.

In the first phase of the smoothing process, the raw optimal shape was curve fit using Microsoft Excel, with the problem coordinates that produced the high-amplitude ROC values omitted from the fit. Those points were then manually modified to lie closer to the interpolated shape, thus greatly reducing the severity of the local ROC variations. The result of this process is depicted in Figure 19. There it is evident that the extreme ROC variations have been reduced quite significantly, producing a much smoother overall behaviour. This result is now much more in keeping with our expectations for an optimal shape, but some further smoothing of the ROC variations is still desirable.

In the second phase of the radius of curvature smoothing process, the techniques reported by Wescott and Heller (2009) were applied to further smooth the notch shape. Two cycles of this automated smoothing were computed, and the ROC results obtained are depicted in Figure 20. The (x, y) coordinates at the two ends of the notch, as well as the (x, y) coordinate associated with the centre of the notch shape, were held fixed during the ROC smoothing process. Because of the manual adjustment of the node coordinates prior to undertaking the next phase of ROC smoothing, the automated ROC smoothing process has been very effective in further reducing the variations in ROC along the notch boundary, even with just two cycles.

Note that this level of ROC smoothing has a very small effect on the stresses in the constant-stress zone. This was checked by creating a new finite element model based on the smoothed coordinates of the optimal boundary. The normalised maximum principal stress for the smoothed notch geometry is shown in Figure 21. Compared to the results for the unsmoothed shape, the corner at approximately x = 25 mm is slightly more rounded, and the extent of the constant stress zone has been reduced a little bit (from x = 25.3 mm to x = 24.8 mm). The arc length of the constant-stress zone for the smoothed notch is 50.3 mm, and this is 1.8% shorter than for the unsmoothed notch.

The smoothed notch coordinates are supplied in Table 1. These were read into MSC Patran and used to generate an IGES file containing a representation of the smoothed optimal notch profile suitable for use in creating commands for computer numerically controlled machining of the coupons. The IGES file format is used to specify the notch boundary as a series of circular arcs and straight line segments. A listing of the contents of the IGES file corresponding to the notch contour for the Modified Constant-Stress Coupon is provided in Appendix G (a copy of this file can also be found in Objective folder fAV1044714, and the name of the file is Al_mod_optimal_3D_msmth_smoothed_002.igs).

It is instructive to compare the smoothing approach used above with the results that are obtained when the original raw unsmoothed coordinates for the Modified Constant-Stress Coupon have been passed through 20 cycles of the automated ROC smoothing algorithm. The resulting ROC variation in the notch region is shown in Figure 22. It is apparent that these results are clearly different from those presented in Figure 20, with the major differences being confined to the central region of the notch, –7 mm ≤ x ≤ +7 mm. The ROC results obtained using 20 cycles of automated smoothing have a peak ROC value that is

about 15% greater. It is considered here that the application of manual plus automated smoothing has produced a smoother overall result, and it is expected that the resulting changes to the shape coordinates will be less than those produced by 20 cycles of automated smoothing.

5. 2D fracture mechanics assessment of modified constant-stress coupon

As the Modified Constant-Stress Coupon will be used in fatigue testing studies involving crack growth, it is instructive to assess its performance from a fracture mechanics perspective. The programs that were used for this analysis are located in Objective folder fAV1044714.

5.1 Analysis of uncracked coupon

Firstly, a full 2D model of the uncracked Modified Constant-Stress Coupon was created for analysis with FADD2D using the coordinates of the node locations in the original finite element model. A full model was needed as this forms the basis for subsequent stress intensity factor calculations associated with the placement of through-thickness edge cracks at various assumed locations distributed along the notch boundary.

The material properties corresponded to those for a typical aluminium alloy, and were the same as before (E = 72.4 GPa and υ = 0.33). Plane stress conditions were specified as the thickness of the specimen is small compared to the other dimensions. The applied load consisted of a uniform tensile pressure applied to the vertical edges at the two ends. To prevent rotation of the grip ends, 6 points were chosen on the grip zone boundary and restrained from moving in the y-direction. Using the (x, y) coordinate system defined in Figure 9, these points were located at (x, y) = (±62 mm, 20 mm), (±62 mm, –20 mm) and (±122 mm, 0 mm). In addition, in order to prevent rigid body motion of the coupon, the point on the boundary at (x, y) = (–122 mm, 0 mm) was restrained from moving in the x-direction.

The FADD2D model was created using the CreateDogboneCouponModel program (see Appendix D), and it was used to compute the maximum principal stress along the optimised notch boundary of the modified constant stress coupon. Figure 23 plots the normalised maximum principal stress obtained from the boundary element model, and compares it to the results obtained from the finite element model that was used during the shape optimisation process. It is evident that the two quite different computational approaches have produced results that are very similar. Using the FADD2D boundary element method, the gross-section SCF is K_{tg} = 2.519, which is almost identical to the value K_{tg} = 2.516 obtained using the finite element method.

5.2 Computation of crack trajectories for edge-cracked coupon

Using the 2D model described above, an edge crack was inserted at various locations along the notch boundary. As a result of the 2D nature of the solution, the edge crack is assumed to be a through crack. In each case, the initial crack length set to be 0.1 mm, which can be regarded as being a very short crack relative to the size of the specimen. At each chosen location, the simulated crack was oriented to be perpendicular to the boundary. This essentially means that the crack was initially aligned to open in a Mode I dominant crack propagation mode, as this was assumed to be representative of what might happen in the coupon during fatigue testing.

For the purposes of this analysis, the cracks are located at different points along the notch boundary with the following *x*-coordinates: 0.00 mm, 4.24 mm, 8.51 mm, 12.74 mm, 16.95 mm, 21.11 mm, 23.17 mm, 25.26 mm, 29.45 mm, and 32.14 mm. These starting points correspond to node locations in the original finite element model. The FADD2D code was used to compute the crack trajectory for a single crack growing from each of these locations. A crack growth increment of 0.1 mm per iteration was used to compute the crack growth trajectory associated with each cracking scenario. For the purpose of this simulation, the cracks were allowed to grow until they had reached 20 mm in length.

The computed crack trajectories obtained for each of the cracks are shown in Figure 24. The trajectories become more curved as the starting location of the crack moves further away from the centre of the coupon. The crack trajectories remain relatively straight in the range of starting locations 0 mm ≤ x ≤ 15 mm.

5.3 Computation of Beta factors for through-thickness edge-cracked coupon

When the crack trajectories were being computed, the FADD2D boundary element code was also calculating the corresponding stress intensity factors, K, for the particular crack geometry that was present at each crack growth increment. It is considered instructive to compare these stress intensity factors to those corresponding to an edge crack of equivalent length that is located in a semi-infinite plate.

For a through-thickness edge crack of length a in a semi-infinite plate subjected to a remote uniaxial tension stress, S_∞, the equation for the stress intensity factor K is

$$K = S_\infty \sqrt{\pi a} F \tag{1}$$

where F is a boundary correction factor (also called a Beta factor). As its name implies, the boundary correction factor accounts for the influence of various boundaries, but it is also often a function of parameters such as crack geometry, crack length, plate width, plate thickness, hole radius (where present), angular position along a crack front, etc. However, for the semi-infinite plate geometry, the boundary correction factor is a constant value,

and is simply F = 1.1215 (Tada, Paris and Irwin 2000; Broek 1978), which is also known as the free-edge correction factor.

For a through-thickness edge crack that is located at any point along the notch boundary of the Modified Constant-Stress Coupon, the stress intensity factor can be written as

$$K = S\sqrt{\pi a}F \tag{2}$$

where S is the local tangential stress at the notch surface, and a is the crack length as measured along the curved crack trajectory. In the constant stress region, S can be computed by using $S = K_{tg} S_\infty$, where K_{tg} is the local gross-section SCF and S_∞ is the remote uniform uniaxial tension stress applied to the ends of the coupon.

Figure 25 shows the boundary correction factors, F, plotted as a function of crack length, a, for a number of cracks starting from different points along the notch boundary. As a point of reference, the crack-length-independent boundary correction factor for a through-thickness edge crack in a semi-infinite plate is represented by the dashed horizontal line (F = 1.1215). For cracks located in the range 0 mm ≤ x ≤ 16.95 mm that have crack lengths a ≤ 2.5 mm, it is apparent that the geometry factor is within about 2% or so of F = 1.1215 for an edge crack in a semi-infinite plate.

The boundary correction factors as a function of distance along the notch boundary for edge cracks of varying lengths for the Modified Constant-Stress Coupon are plotted in Figure 26. The boundary correction factor for very short cracks, a ≤ 0.1 mm, is within 1.0% of the theoretical edge crack solution, F = 1.1215, over the entire length of the constant stress region. For short cracks, a ≤ 1.0 mm, the boundary correction factor is within 3.3% of F = 1.1215 along 84% of the constant-stress region, dropping by 7.5% at the end of the constant-stress zone.

5.4 Computation of Beta factors for other crack geometries

From the data presented in Figure 25 and Figure 26, the stress intensity factors for short through-thickness edge cracks for the constant stress specimen are largely in agreement with the solution for an edge crack in a semi-infinite plate. By analogy, it would therefore be expected that stress intensity factors for other types of short cracks (e.g. circular or elliptical corner cracks, circular or elliptical surface cracks, etc.) would be well represented by their nominal solutions computed for geometries that are similar to that of the constant-stress coupon. For example, if so desired, the stress intensity factor equations for planar semi-elliptical surface and corner flaws published by Broek could be utilised (Broek 1978, Section 3.6, Elliptical cracks). Hence, for many types of small (short) natural flaws, the body of existing stress intensity factor solutions can be taken advantage of, thus circumventing the need for computation of new sets of solutions that are specific to the present coupon geometry and loading.

6. Conclusion

The coordinates of the smoothed notch profile for the new Modified Constant-Stress Coupon were presented in Table 1. These have also been made available as an IGES file, which can be utilised for manufacturing of the coupons using numerically-controlled machining equipment. A listing of the contents of the IGES file is given in Appendix G, and a copy of the file can be found in Objective folder fAV1044714 (the name of the file is Al_mod_optimal_3D_msmth_smoothed_002.igs).

A summary of the dimensions of the Modified Constant-Stress Coupon, together with those of the original design, is presented in Table 2. It is noted that the grip area of the Modified Constant-Stress Coupon has been increased by 225% over the original constant-stress coupon design. Together with the increase in gross-section SCF resulting from the increase in the total width of the coupon, the incidences of specimen failure in the grip zone are expected to be greatly reduced, if not entirely eliminated. The arc length of the constant-stress zone in the Modified Constant-Stress Coupon is approximately 7.5% less than that which was obtained for the original constant-stress coupon. If required, a closer match could be attained by increasing the length of the notch zone and/or reducing the depth of the notch.

Using a 2D boundary element model of the Modified Constant-Stress Coupon, a number of potential crack growth trajectories have been computed by using the FADD2D fracture analysis code to perform simulations of 2D through-thickness edge cracks. The starting locations of the edge cracks were distributed along the constant-stress zone of the notch boundary. As the cracking location moved away from the centre of the coupon, the computed crack trajectories progressively became more curved. In the event that cracks that develop in the coupons are allowed to grow to a long length, it would be interesting to compare the crack growth trajectories obtained from fatigue testing with their computationally-determined counterparts.

7. Acknowledgement

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Table 1: Coordinates of the smoothed optimal profile for Modified Constant-Stress Coupon. (See Figure 9 for definition of the x-y coordinate system.)

Point	x (mm)	y (mm)	Point	x (mm)	y (mm)
1	0.0000	12.5000	42	22.7246	15.0170
2	0.5594	12.5011	43	23.2598	15.1800
3	1.1188	12.5044	44	23.7921	15.3519
4	1.6782	12.5098	45	24.3211	15.5338
5	2.2376	12.5175	46	24.8464	15.7263
6	2.7969	12.5273	47	25.3673	15.9302
7	3.3562	12.5394	48	25.8825	16.1481
8	3.9154	12.5538	49	26.3911	16.3812
9	4.4746	12.5704	50	26.8926	16.6292
10	5.0337	12.5894	51	27.3867	16.8914
11	5.5927	12.6109	52	27.8732	17.1676
12	6.1516	12.6347	53	28.3515	17.4577
13	6.7104	12.6612	54	28.8213	17.7614
14	7.2691	12.6902	55	29.2822	18.0785
15	7.8276	12.7218	56	29.7337	18.4088
16	8.3860	12.7562	57	30.1754	18.7522
17	8.9442	12.7935	58	30.6069	19.1082
18	9.5021	12.8336	59	31.0278	19.4766
19	10.0599	12.8767	60	31.4378	19.8572
20	10.6174	12.9230	61	31.8365	20.2497
21	11.1746	12.9726	62	32.2235	20.6537
22	11.7315	13.0254	63	32.5984	21.0688
23	12.2881	13.0817	64	32.9610	21.4948
24	12.8443	13.1416	65	33.3110	21.9313
25	13.4001	13.2052	66	33.6479	22.3778
26	13.9554	13.2727	67	33.9717	22.8340
27	14.5103	13.3441	68	34.2819	23.2996
28	15.0646	13.4197	69	34.5783	23.7740
29	15.6182	13.4996	60	34.8608	24.2569
30	16.1713	13.5839	71	35.1291	24.7478
31	16.7236	13.6728	72	35.3830	25.2462
32	17.2751	13.7665	73	35.6224	25.7519
33	17.8257	13.8652	74	35.8470	26.2642
34	18.3754	13.9690	75	36.0569	26.7827
35	18.9241	14.0783	76	36.2519	27.3071
36	19.4715	14.1933	77	36.4318	27.8368
37	20.0178	14.3141	78	36.5966	28.3714
38	20.5626	14.4411	79	36.7463	28.9104
39	21.1059	14.5745	80	36.8808	29.4534
40	21.6474	14.7147	81	37.0000	30.0000
41	22.1871	14.8621			

Table 2: Summary of the dimensions and K_t properties of the new Modified Constant-Stress Coupon, together with those of the original design.

	Original Constant-Stress Coupon	Modified Constant-Stress Coupon
Thickness (mm)	6.35	6.35
Total length (mm)	160	244
Total width (mm)	40	60
Notch length (mm)	70	74
Width of centre-section (mm)	25	25
Grip area (mm^2)	40×40 = 1600	60×60 = 3600
Grip buffer zone (mm)	5	25
Arc length of notch boundary (mm)	73.9	89.5
Arc length of constant-stress zone (mm)	54.4	50.3
Net-section SCF K_t	1.038	1.048
Gross-section SCF K_{tg}	1.660	2.516

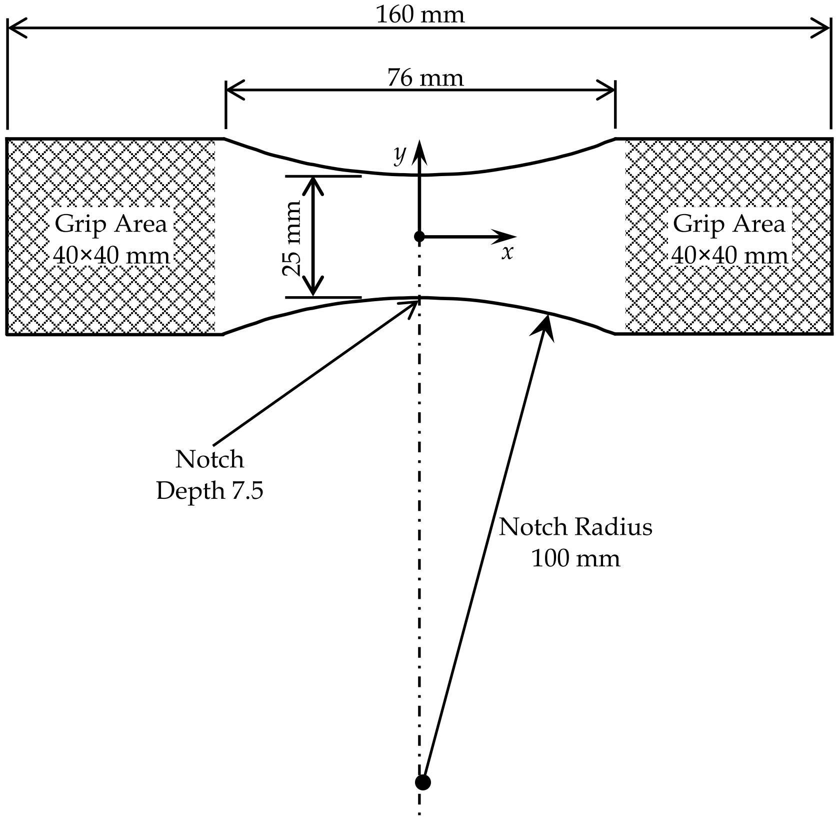

Figure 1: Dimensions of a fatigue test coupon with a constant-radius notch (McDonald 2009a).

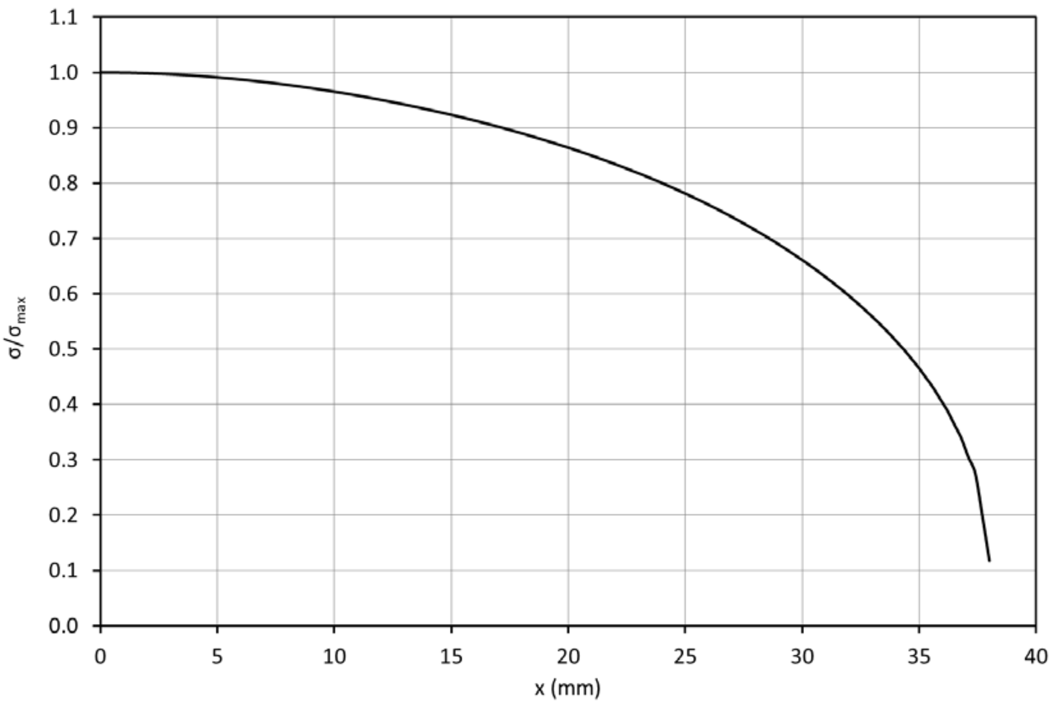

Figure 2: Tangential stress response over the notch region of a fatigue test coupon with a constant-radius notch.

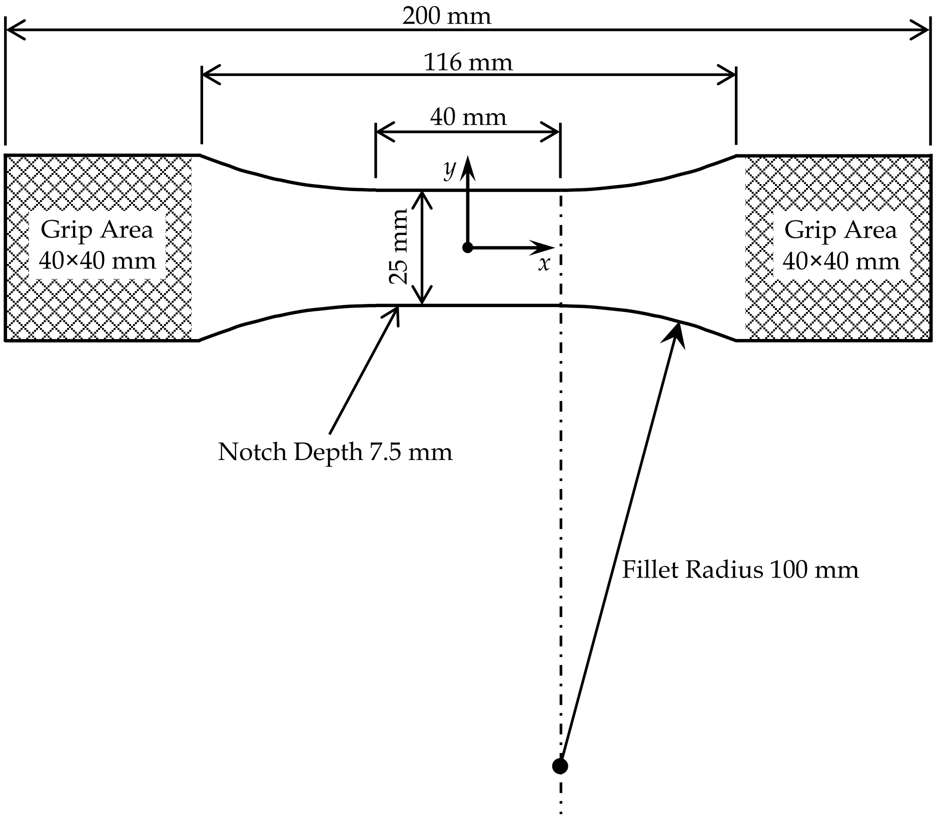

Figure 3: Dimensions of a fatigue test coupon with a central region of constant width and large constant-radius fillets.

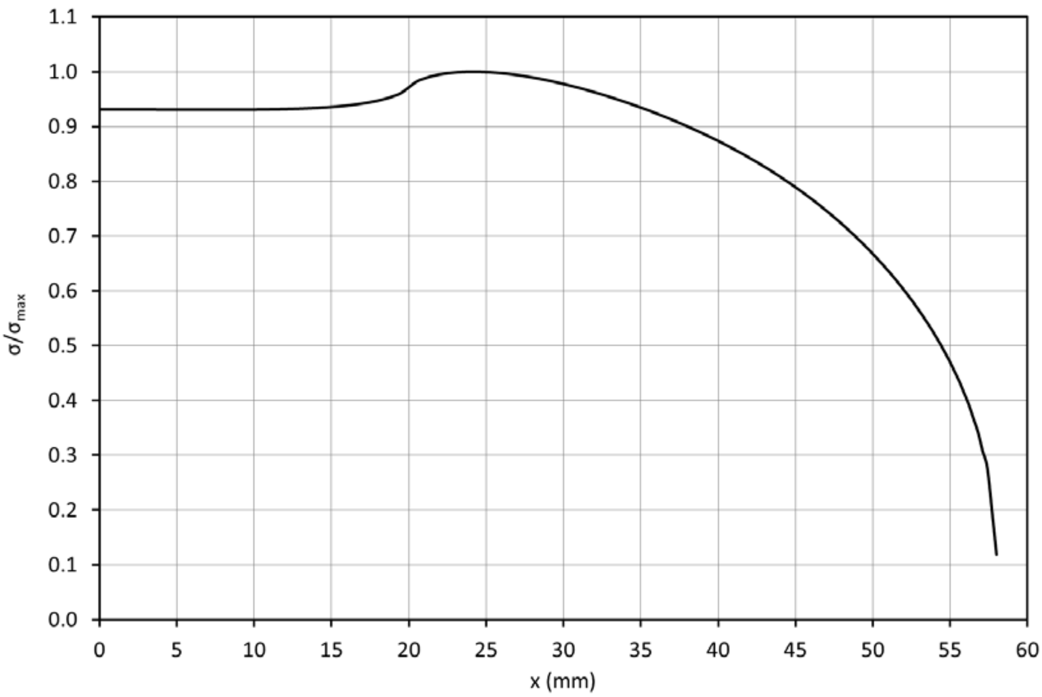

Figure 4: Tangential stress response over the notch region of a fatigue test coupon with a central region of constant width and large constant-radius fillets.

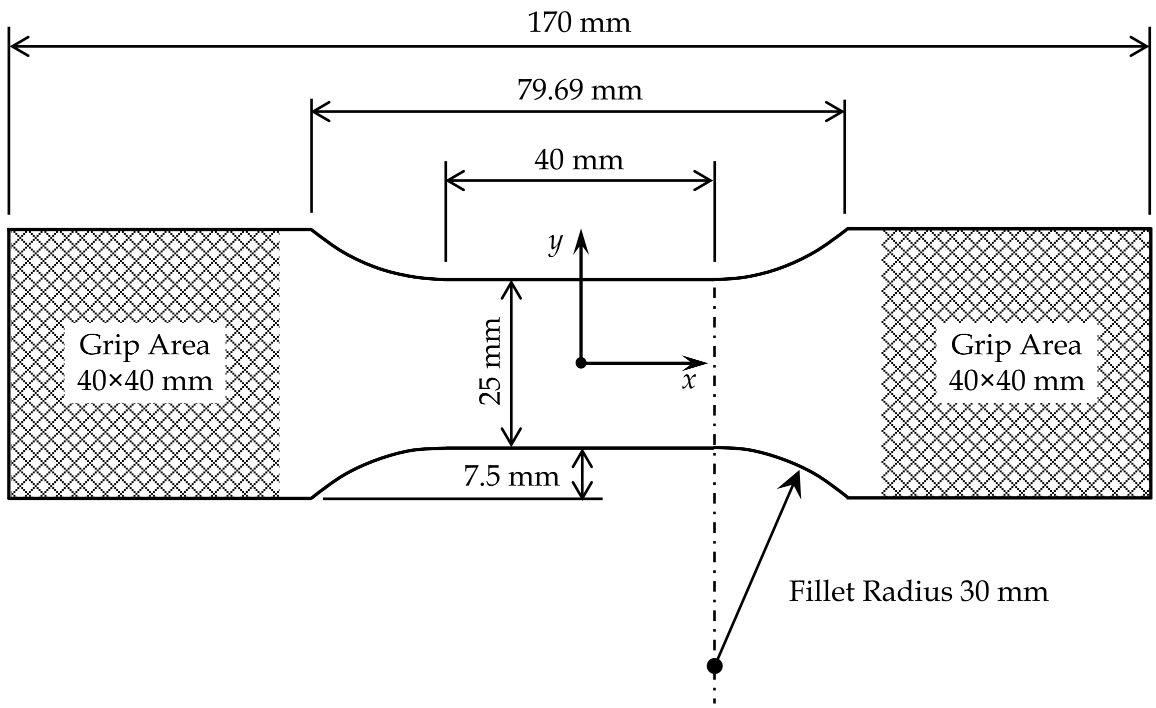

Figure 5: Dimensions of a fatigue test coupon with a central region of constant width and moderate constant-radius fillets.

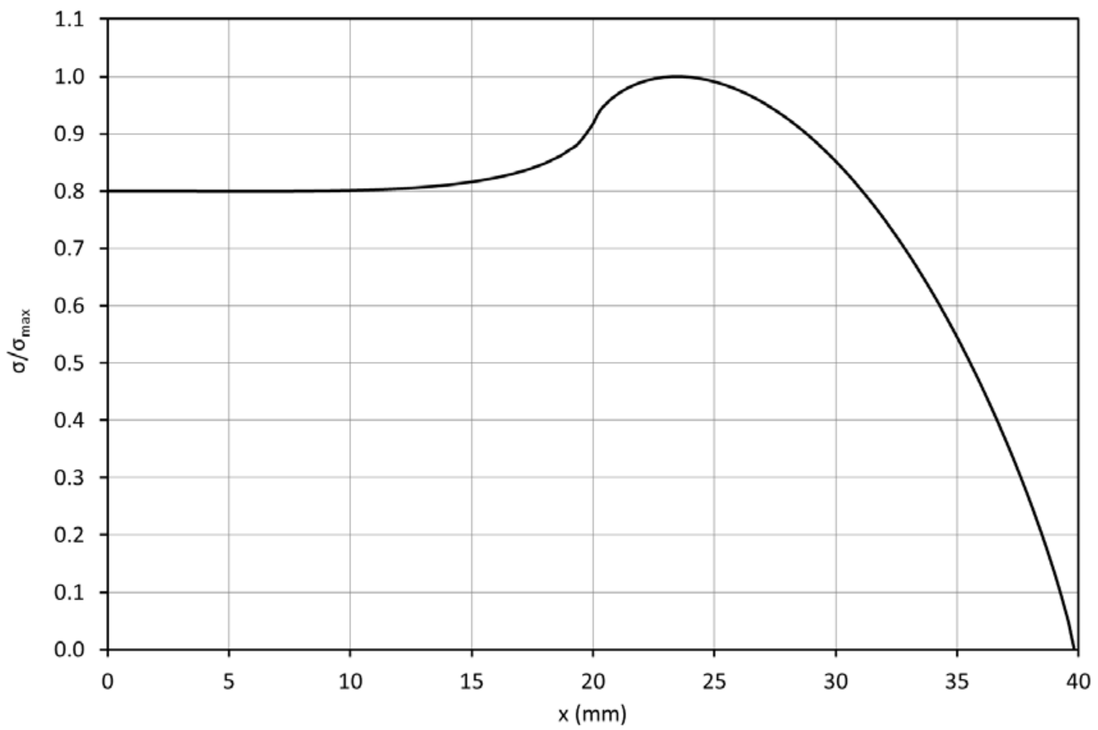

Figure 6: Tangential stress response over the notch region of a fatigue test coupon with a central region of constant width and moderate constant-radius fillets.

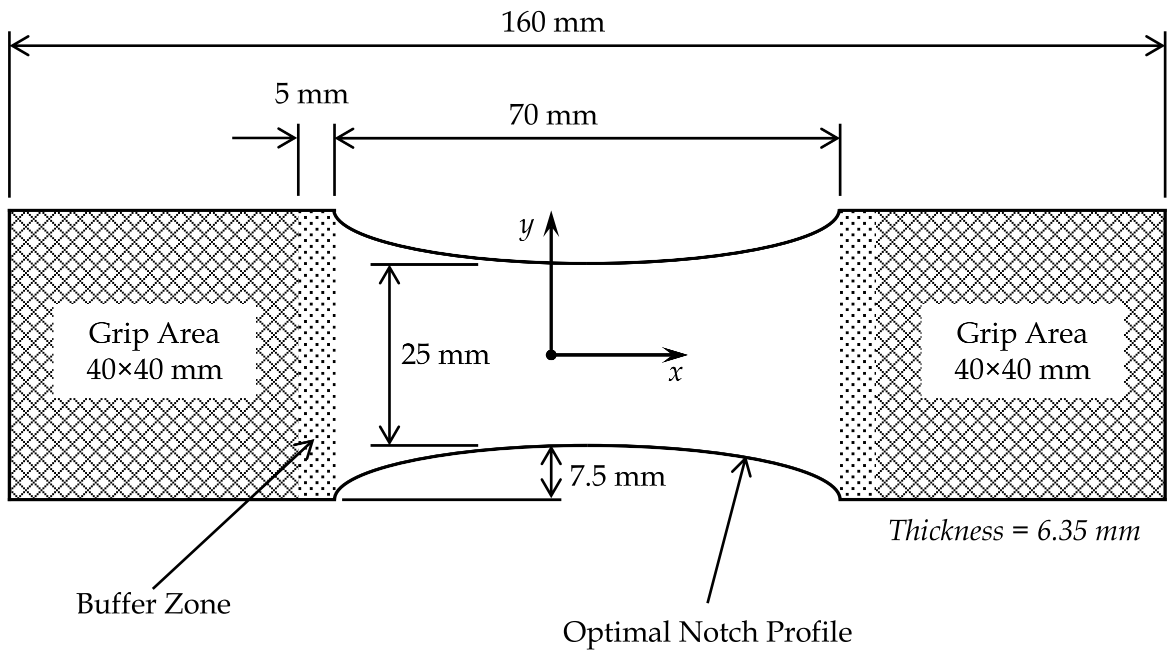

Figure 7: General shape and dimensions of original optimised constant-stress coupon.

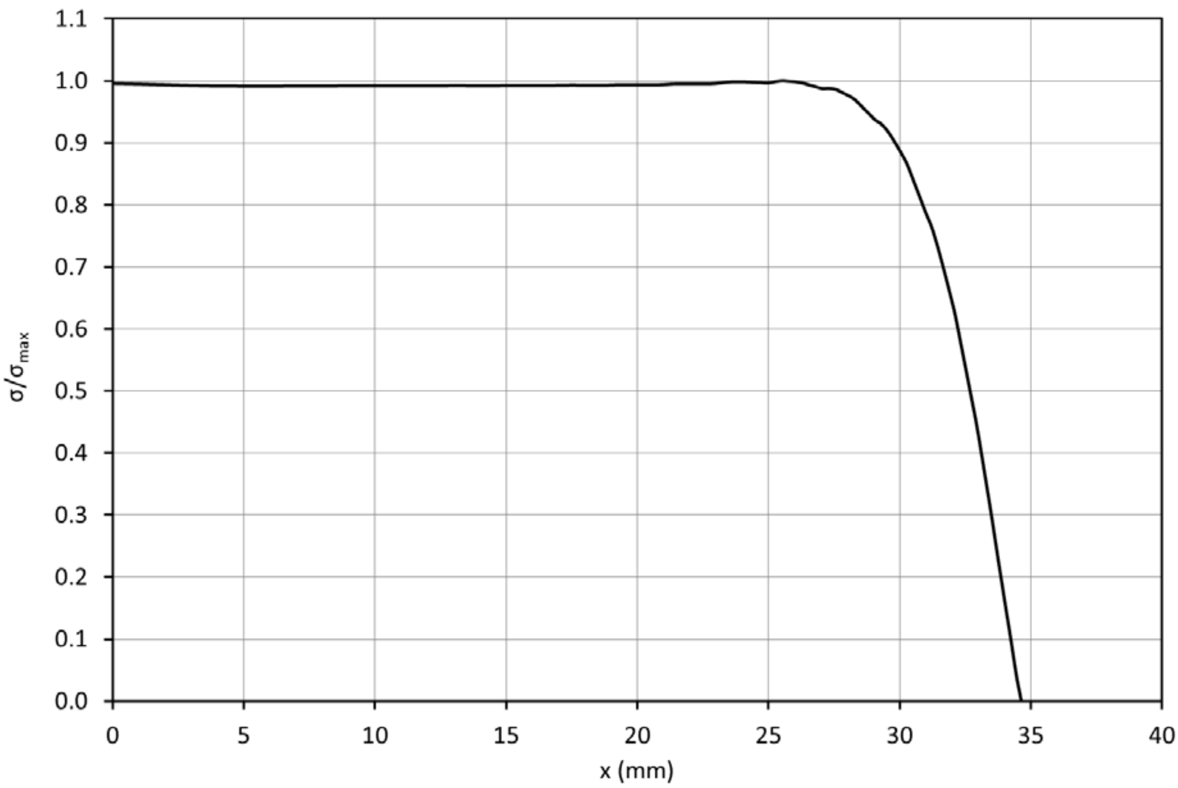

Figure 8: Tangential stress response over the notch region of original optimised constant-stress coupon.

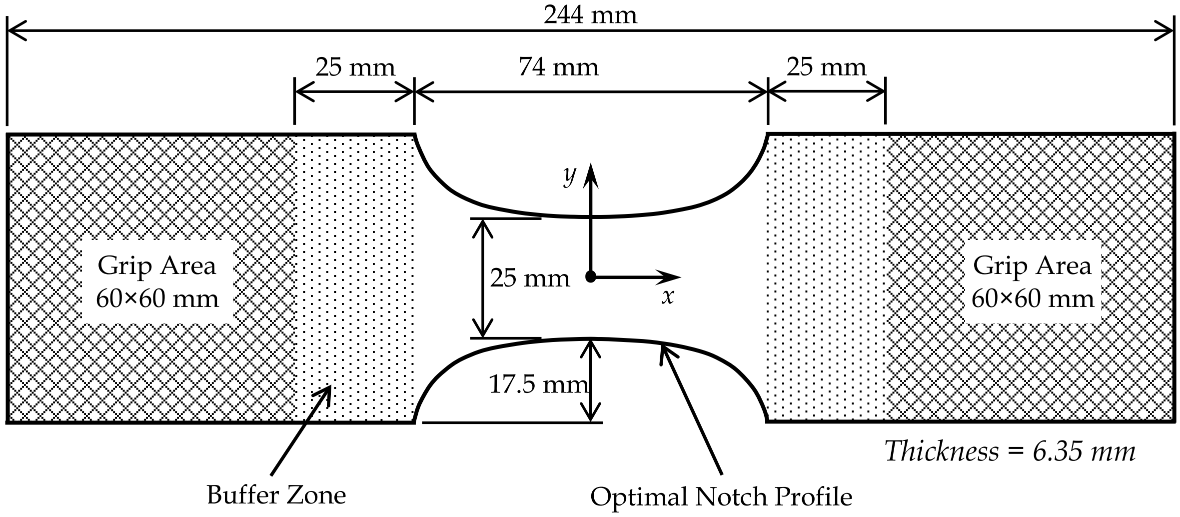

Figure 9: General shape and dimensions of the Modified Constant-Stress Coupon.

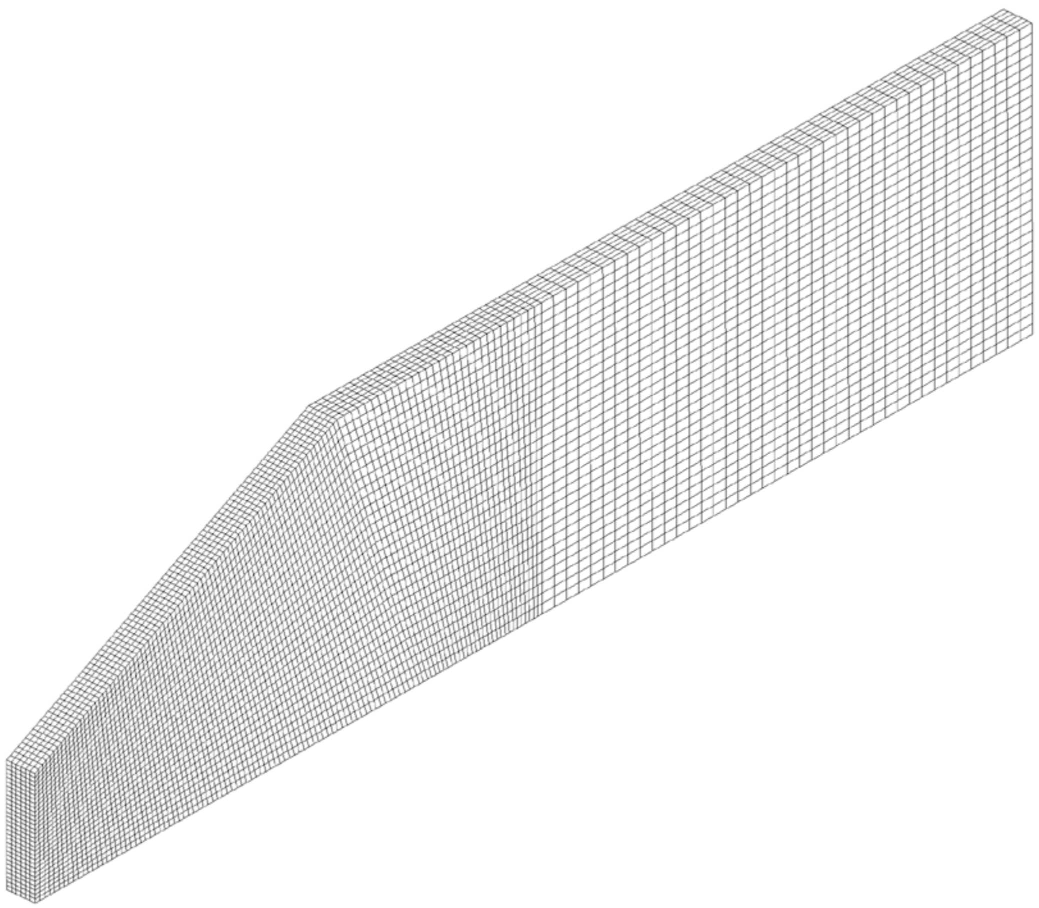

Figure 10: Initial finite element mesh for ⅛-symmetry model of the Modified Constant-Stress Coupon prior to shape optimisation.

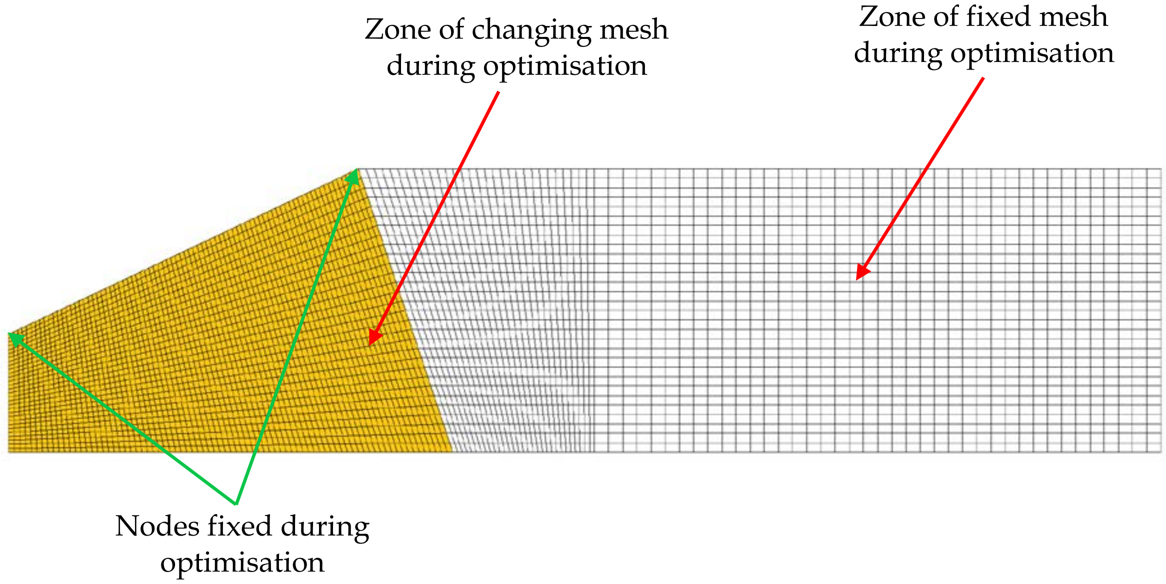

Figure 11: Side view of 3D mesh showing the assumed starting shape of the notch and the optimisation zone.

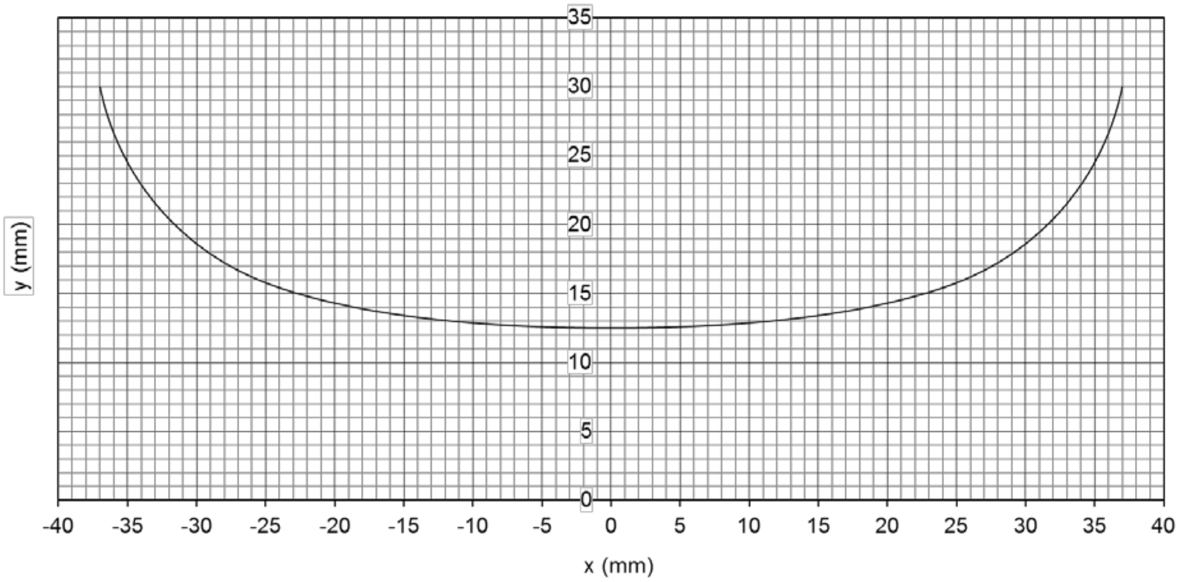

Figure 12: Notch profile optimal shape for the Modified Constant-Stress Coupon.

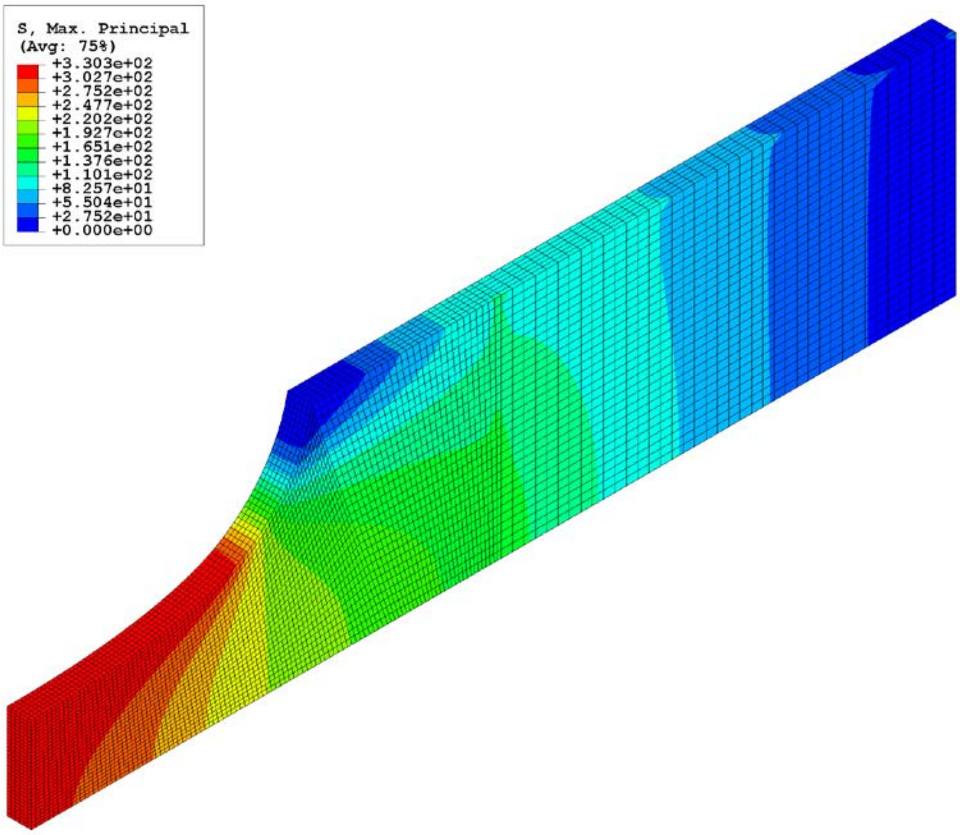

Figure 13: Contours of maximum principal stress for the optimised constant-stress coupon.

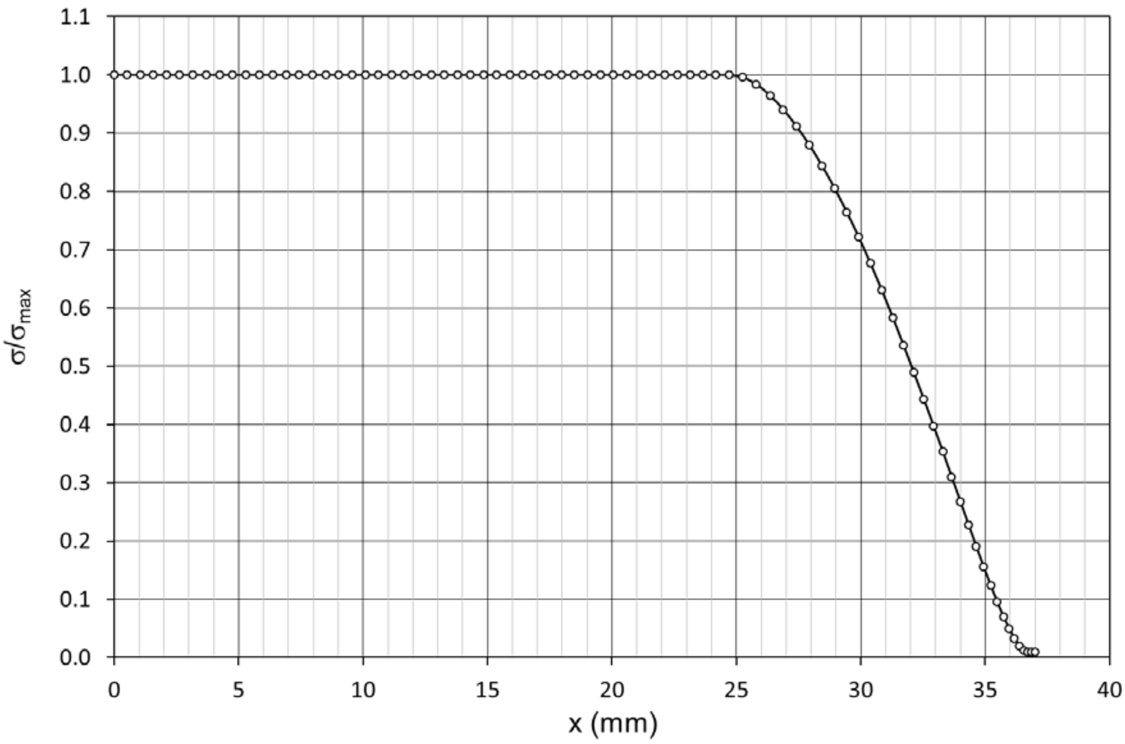

Figure 14: Normalised maximum principal stress along optimal notch boundary for the Modified Constant-Stress Coupon.

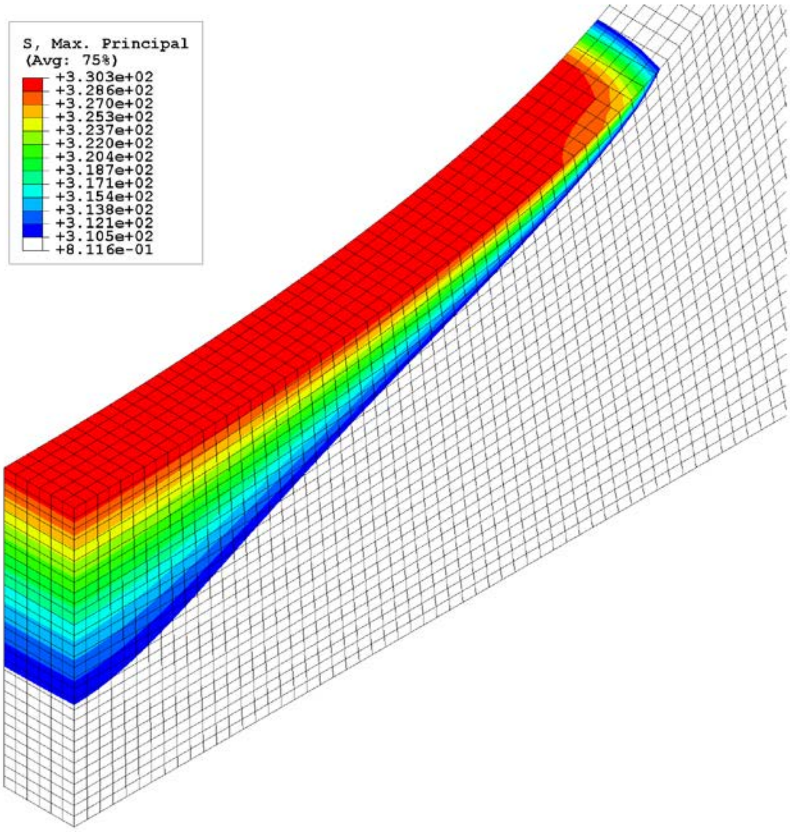

Figure 15: Contours of maximum principal stress in the vicinity of constant-stress region of the optimised Modified Constant-Stress Coupon that are within 6% of the maximum stress.

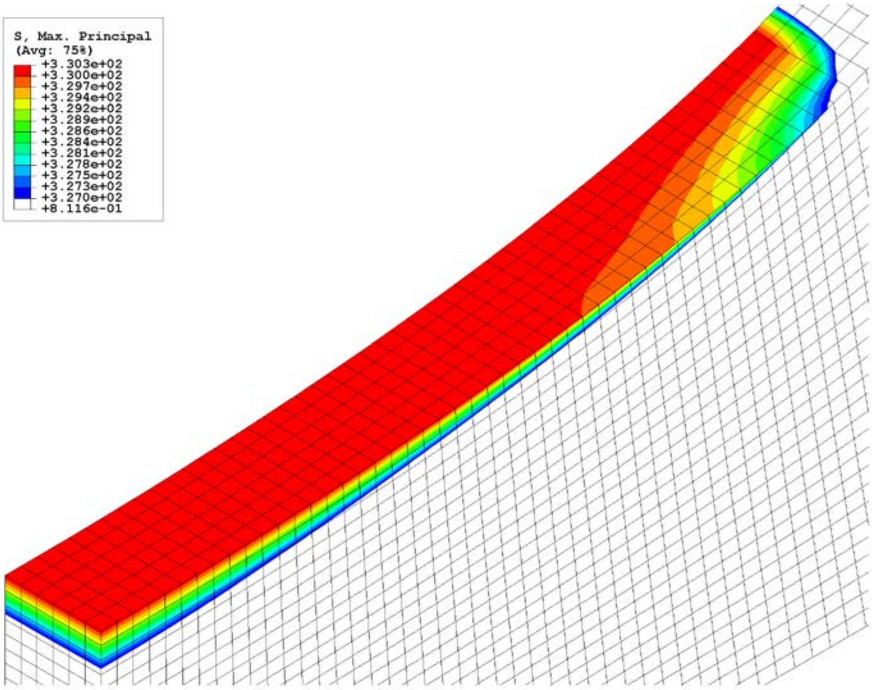

Figure 16: Contours of maximum principal stress in the vicinity of the constant-stress region of the optimised Modified Constant-Stress Coupon that are within 1% of the maximum stress.

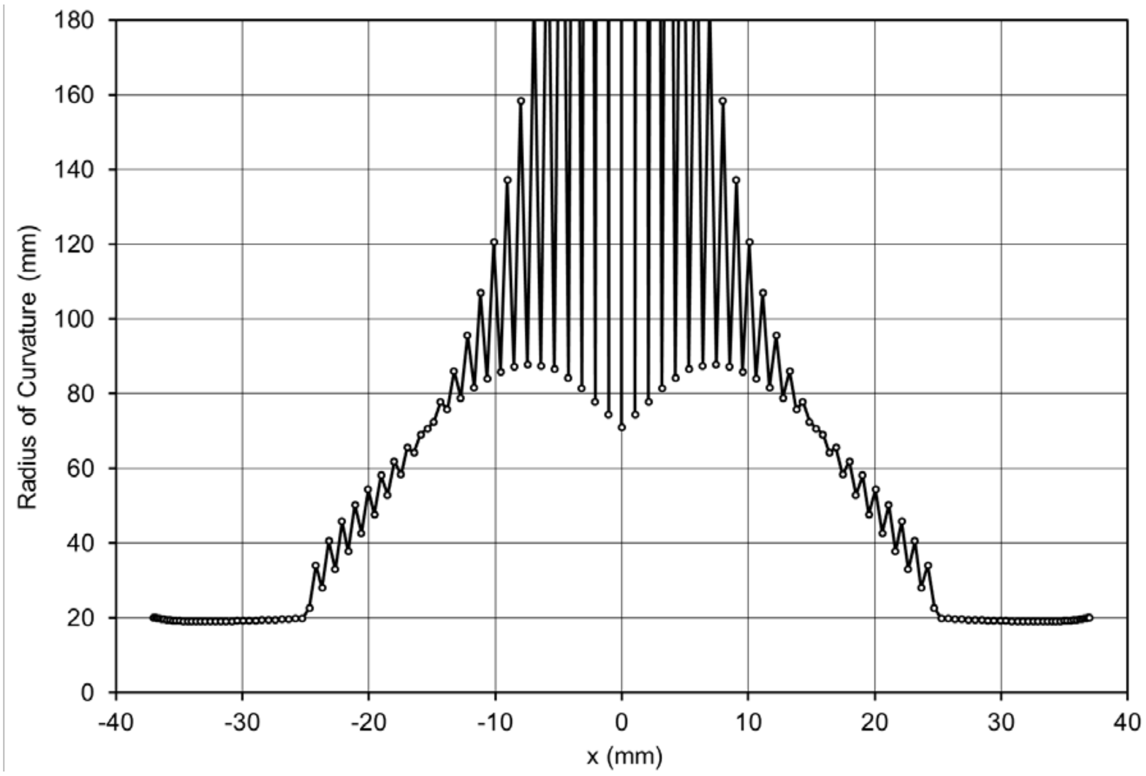

Figure 17: Computed radius of curvature along the raw unsmoothed optimal boundary of the Modified Constant-Stress Coupon.

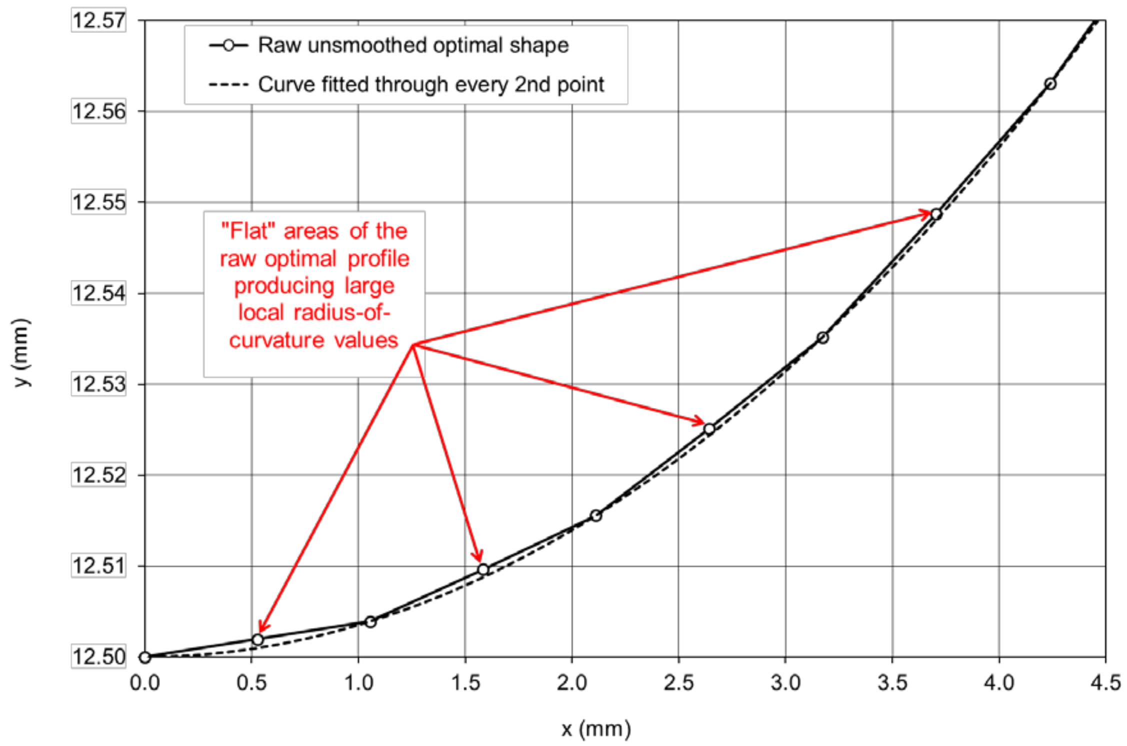

Figure 18: Section of raw unsmoothed optimal profile showing "flat" spots and a more representative smooth curve passing through every second point.

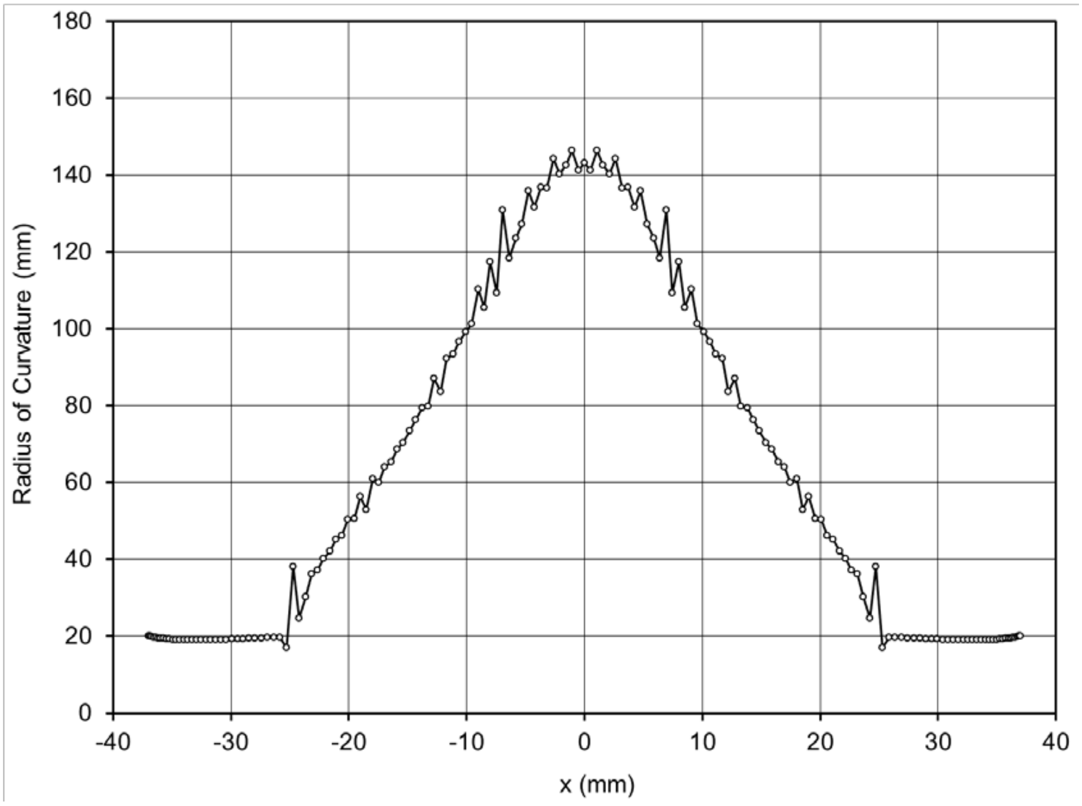

Figure 19: Radius of curvature along the notch boundary after completion of manual smoothing.

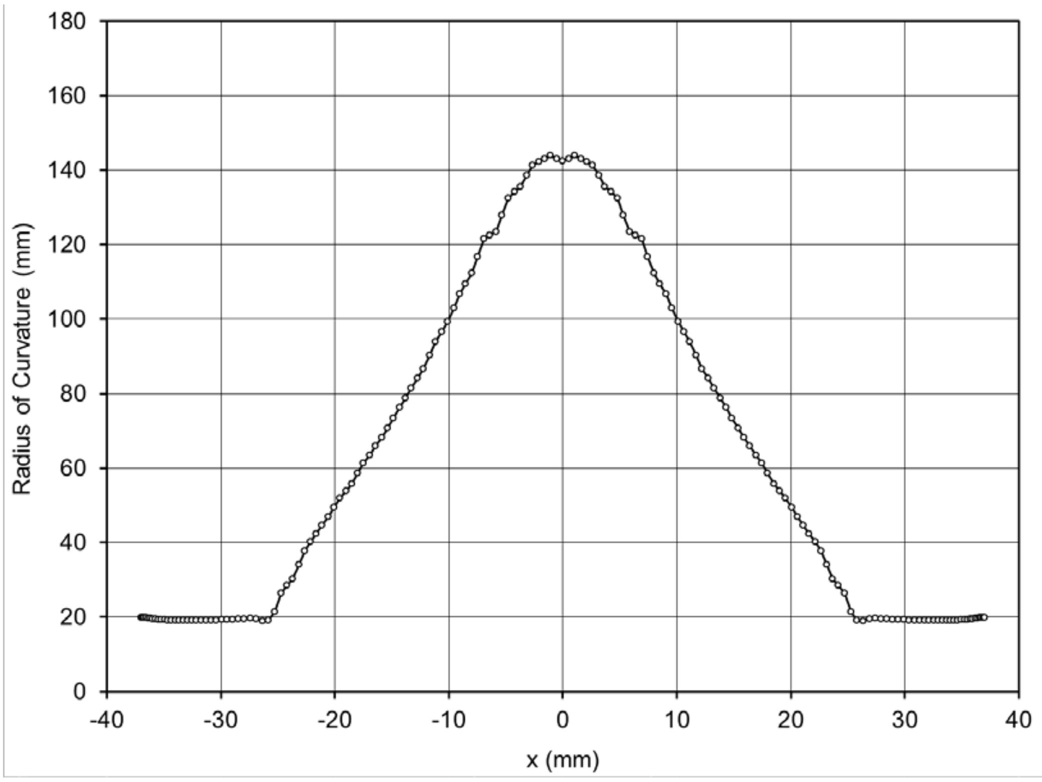

Figure 20: Radius of curvature along the notch boundary after completion of an additional two cycles of automated smoothing.

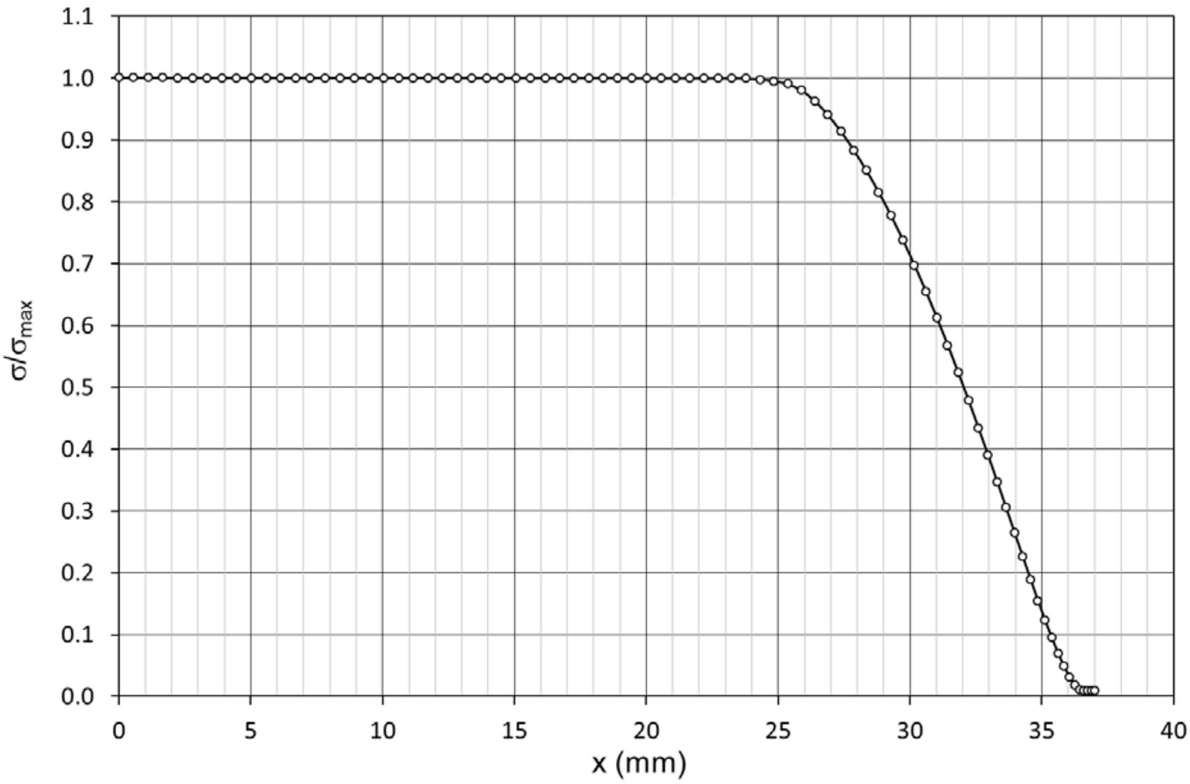

Figure 21: Normalised maximum principal stress along smoothed optimal notch boundary for the Modified Constant-Stress Coupon.

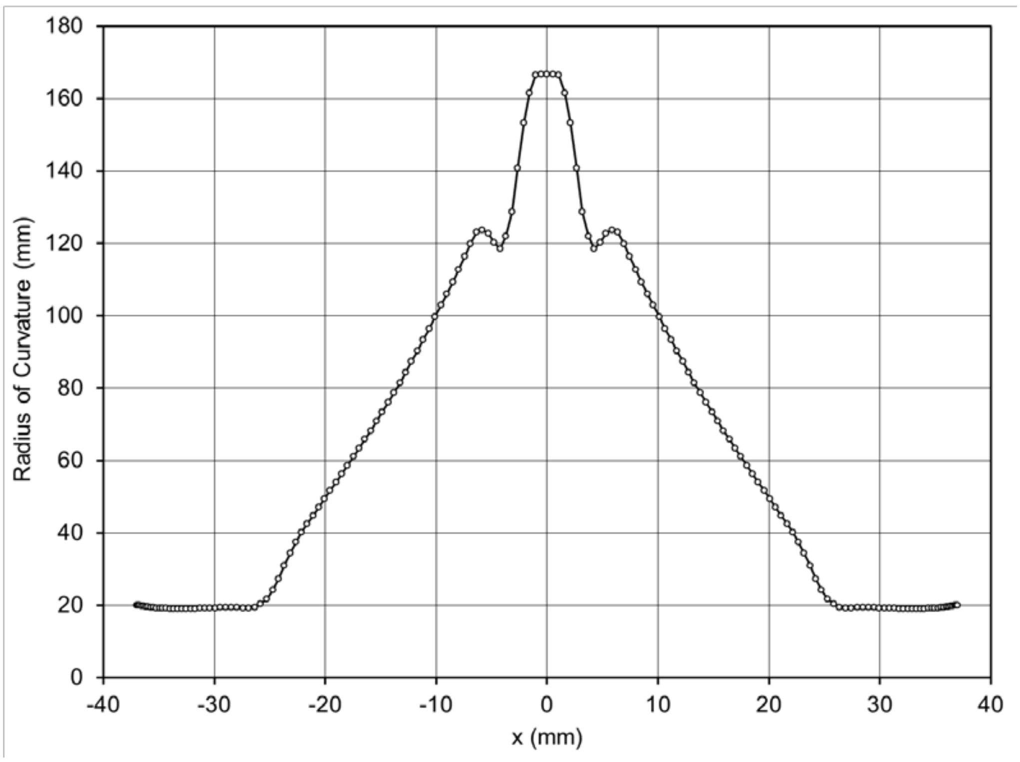

Figure 22: Radius of curvature along the notch boundary after completion of twenty cycles of automated smoothing without applying any prior manual smoothing.

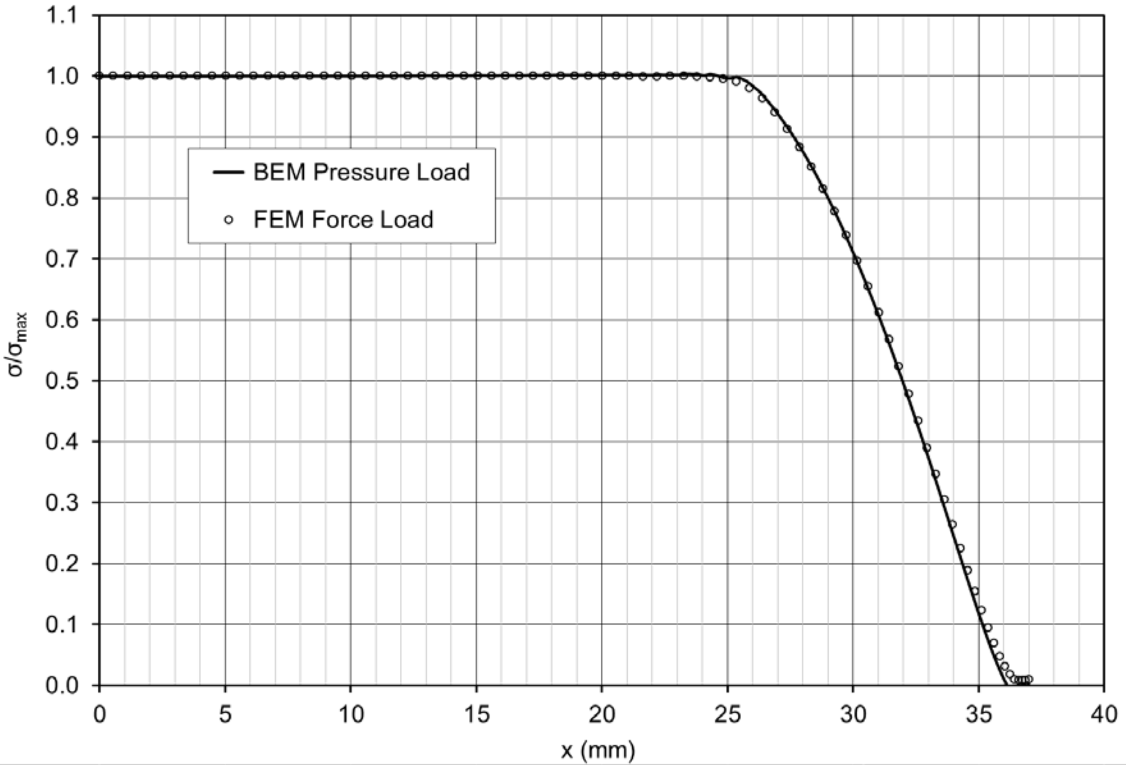

Figure 23: Normalised maximum principal stress along optimal notch boundary for the Modified Constant-Stress Coupon obtained using boundary element and finite element models.

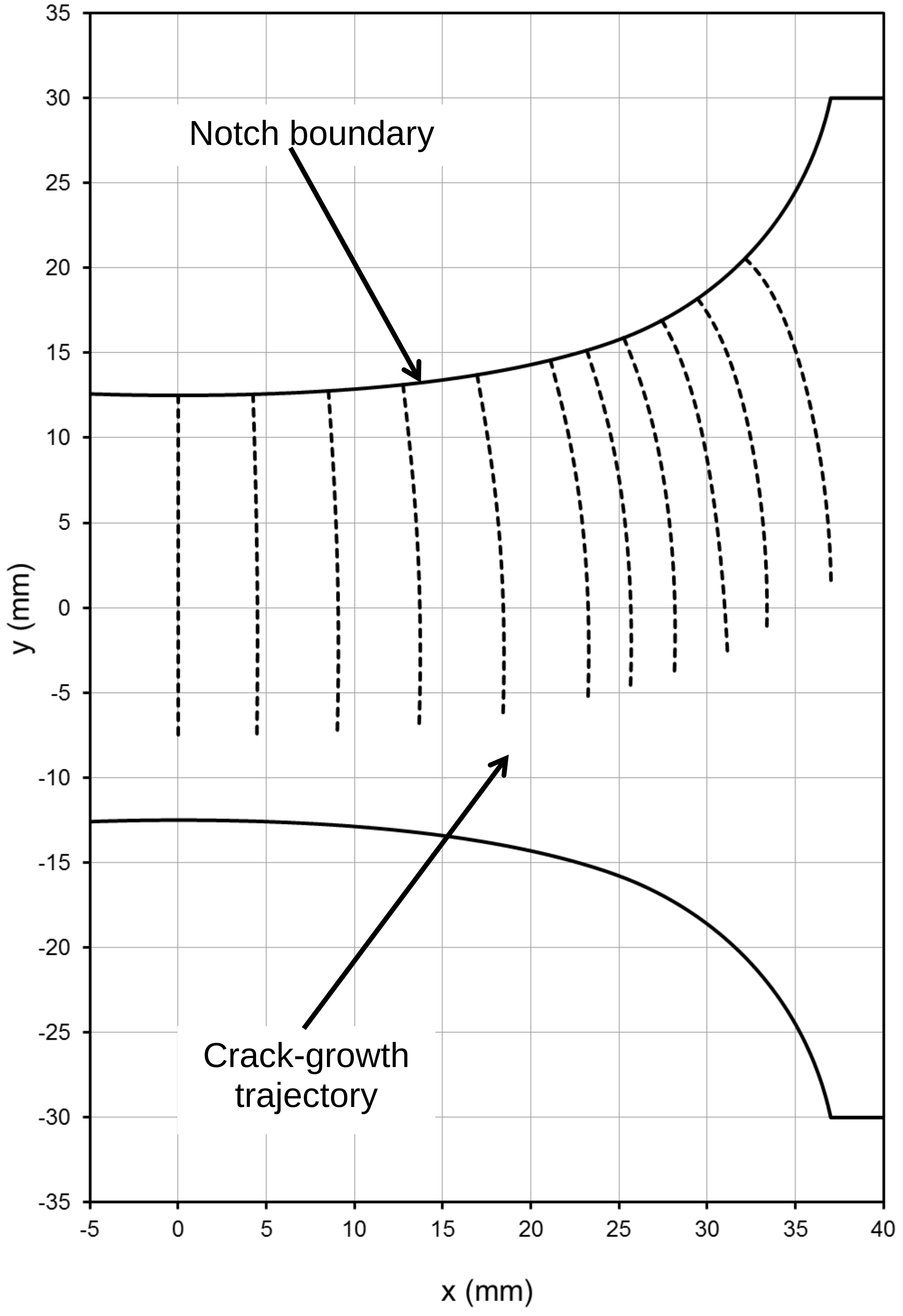

Figure 24: Simulated crack-growth trajectories for through-thickness edge cracks starting from different points along the notch boundary of the Modified Constant-Stress Coupon.

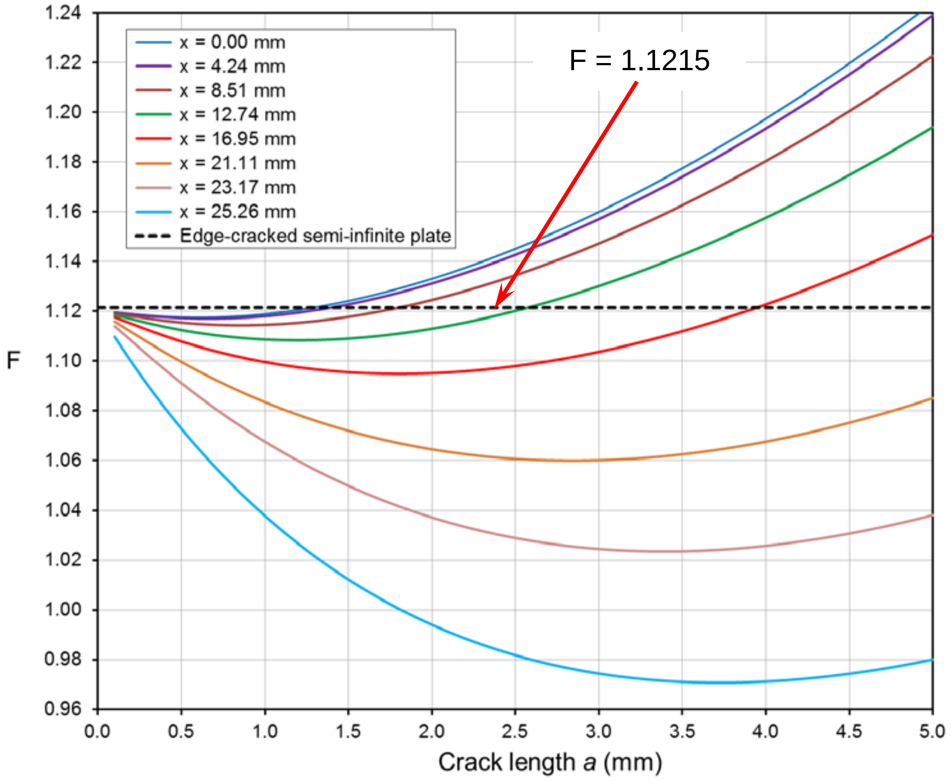

Figure 25: Boundary correction factors as a function of crack length for cracks starting at different points along the notch boundary of the Modified Constant-Stress Coupon.

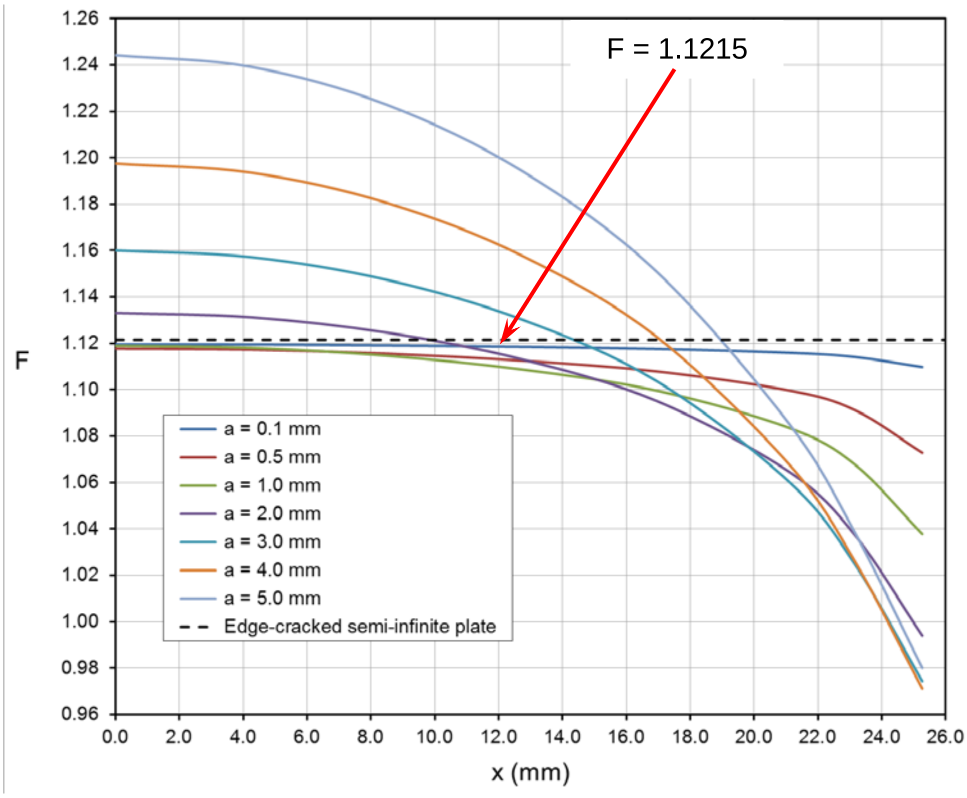

Figure 26: Boundary correction factors as a function of distance along the notch boundary for cracks of varying lengths for the Modified Constant-Stress Coupon.

Appendix A:

FADD2D input file for uncracked notch composed of large 100-mm constant-radius arcs

The following input file can also be found stored in Objective folder fAV1044714.

```
FADD - Visual C++ Version 1.0 - 09/10/14
Dog-bone Fatigue Test Coupon
Constant R = 100 mm Radius Notch
-------------------------------------------------------
Problem Type, No of Materials
2 1
Materials, Elastic modulus, and Poisson's ratio
1 72400.000000 0.330000
Material, Cracks, Boundaries, and Point loads
1 0 1 0
 Input echo, Boundary Stresses, and Displacements
1 1 1

-------------------------------------------------------
Definition of Boundary

1 1
0 0 5

1 0 0.000000 112.500000 100.000000 60
 -90.000000 -1 0.000000 -1 0.000000 0
-101.165823 -1 0.000000 -1 0.000000 0
-112.331645 -1 0.000000 -1 0.000000 0

2 1 30
-37.996710 20.000000 -1 0.000000 -1 0.000000 0
-58.998355 20.000000 -1 0.000000 -1 0.000000 0
-80.000000 20.000000 -1 0.000000 -1 0.000000 0

3 1 30
-80.000000 20.000000 -1 -100.000000 -1 0.000000 0
-80.000000 10.000000 -1 -100.000000 -1 0.000000 0
-80.000000  0.000000 -1 -100.000000 -1 0.000000 0

4 1 40
-80.000000 0.000000 -1 0.000000 0 0.000000 0
-40.000000 0.000000 -1 0.000000 0 0.000000 0
  0.000000 0.000000 -1 0.000000 0 0.000000 0

5 1 40
0.000000  0.000000 0 0.000000 -1 0.000000 0
0.000000  6.250000 0 0.000000 -1 0.000000 0
0.000000 12.500000 0 0.000000 -1 0.000000 0

-------------------------------------------------------
```

Appendix B:

FADD2D input file for uncracked notch with constant central width and large 100-mm radius fillets

The following input file can also be found stored in Objective folder fAV1044714.

```
FADD - Visual C++ Version 1.0 - 09/10/14
Dog-bone Fatigue Test Coupon
40 mm Uniform Section With R = 100 mm Radius Fillets
-------------------------------------------------------
Problem Type, No of Materials
2 1
Materials, Elastic modulus, and Poisson's ratio
1 72400.000000 0.330000
Material, Cracks, Boundaries, and Point loads
1 0 1 0
 Input echo, Boundary Stresses, and Displacements
1 1 1

-------------------------------------------------------
Definition of Boundary

1 1
0 0 6

1 1 30
  0.000000 12.500000 -1 0.000000 -1 0.000000 0
-10.000000 12.500000 -1 0.000000 -1 0.000000 0
-20.000000 12.500000 -1 0.000000 -1 0.000000 0

2 0 -20.000000 112.500000 100.000000 60
 -90.000000 -1 0.000000 -1 0.000000 0
-101.165823 -1 0.000000 -1 0.000000 0
-112.331645 -1 0.000000 -1 0.000000 0

3 1 30
 -57.996710 20.000000 -1 0.000000 -1 0.000000 0
 -78.998355 20.000000 -1 0.000000 -1 0.000000 0
-100.000000 20.000000 -1 0.000000 -1 0.000000 0

4 1 30
-100.000000 20.000000 -1 -100.000000 -1 0.000000 0
-100.000000 10.000000 -1 -100.000000 -1 0.000000 0
-100.000000  0.000000 -1 -100.000000 -1 0.000000 0

5 1 40
-100.000000 0.000000 -1 0.000000 0 0.000000 0
 -50.000000 0.000000 -1 0.000000 0 0.000000 0
   0.000000 0.000000 -1 0.000000 0 0.000000 0

6 1 40
0.000000  0.000000 0 0.000000 -1 0.000000 0
```

```
0.000000  6.250000 0 0.000000 -1 0.000000 0
0.000000 12.500000 0 0.000000 -1 0.000000 0

-------------------------------------------------------
```

Appendix C:

FADD2D input file for uncracked notch with constant central width and medium 30-mm radius fillets

The following input file can also be found stored in Objective folder fAV1044714.

```
FADD - Visual C++ Version 1.0 - 09/10/14
Dog-bone Fatigue Test Coupon
40 mm Uniform Section With R = 100 mm Radius Fillets
------------------------------------------------------
Problem Type, No of Materials
2 1
Materials, Elastic modulus, and Poisson's ratio
1 72400.000000 0.330000
Material, Cracks, Boundaries, and Point loads
1 0 1 0
 Input echo, Boundary Stresses, and Displacements
1 1 1 1

------------------------------------------------------
Definition of Boundary

1 1
0 0 6

1 1 30
  0.000000 12.500000 -1 0.000000 -1 0.000000 0
-10.000000 12.500000 -1 0.000000 -1 0.000000 0
-20.000000 12.500000 -1 0.000000 -1 0.000000 0

2 0 -20.000000 42.500000 30.000000 60
 -90.000000 -1 0.000000 -1 0.000000 0
-110.704811 -1 0.000000 -1 0.000000 0
-131.409622 -1 0.000000 -1 0.000000 0

3 1 30
-39.843134 20.000000 -1 0.000000 -1 0.000000 0
-62.421567 20.000000 -1 0.000000 -1 0.000000 0
-85.000000 20.000000 -1 0.000000 -1 0.000000 0

4 1 30
-85.000000 20.000000 -1 -100.000000 -1 0.000000 0
-85.000000 10.000000 -1 -100.000000 -1 0.000000 0
-85.000000  0.000000 -1 -100.000000 -1 0.000000 0

5 1 40
-85.000000 0.000000 -1 0.000000 0 0.000000 0
-42.500000 0.000000 -1 0.000000 0 0.000000 0
  0.000000 0.000000 -1 0.000000 0 0.000000 0

6 1 40
0.000000  0.000000 0 0.000000 -1 0.000000 0
```

```
0.000000  6.250000 0 0.000000 -1 0.000000 0
0.000000 12.500000 0 0.000000 -1 0.000000 0

-------------------------------------------------------
```

Appendix D:

Fortran 90 source code for the CreateDogboneCouponModel program

The following source code can also be found stored in Objective folder fAV1044714.

```
!==============================================================================
!
!  PROGRAM: CreateDogboneCouponModel
!
!  PURPOSE: To take a set of points that define the curved boundary and outer
!           geometry of a dog-bone specimen and create a FADD2D model. Two
!           models are created, one with and the other without an edge crack.
!
!  AUTHOR:  Witold Waldman
!
!  DATE:    2014-08-04
!
!=============================================================================

program CreateDogboneCouponModel

call DogboneCouponModel(.TRUE.)
call DogboneCouponModel(.FALSE.)

end program CreateDogboneCouponModel

!=============================================================================

subroutine DogboneCouponModel(cracked)

!
!       |#------------------------ l ----------------------------#|
!
!      B03     B02      B01                     B14      B13     B12
!  <--- +-------Y--------+                       +--------Y-------+ ---> ----
!  <--- |                 \                     /Cn               | --->   #
!  <--- |                   \________+________/                   | --->   |
!  <--- |                            C1                           | --->   |
!  <--- |                                                         | --->   |
!  <--- XY B04                       + (x,y) origin          B11 Y ---> h
!  <--- |                                                         | --->   |
!  <--- |                    ________+_______                     | --->   |
!  <--- |                   /                 \                   | --->   |
!  <--- |                 /                     \                 | --->   #
!  <--- +-------Y--------+                       +--------Y-------+ ---> ----
!      B05     B06      B07                     B08      B09     B10
!
implicit none

integer(4), parameter :: lui    = 1
```

```
integer(4), parameter :: luo    = 2
integer(4), parameter :: nb     = 14
integer(4), parameter :: ndash  = 86
integer(4), parameter :: maxpts = 1000
real(8)   , parameter :: px     = 100.0d0

logical(4) cracked

character  str(100)*128,filedbi*32,filedbc*32,filedbu*32
integer(4) nc,ncracks,nelemcrack
real(8)    cx(maxpts),cy(maxpts)
real(8)    bx(nb),by(nb)
integer(4) id,ic,i,j,nelem
integer(4) icrackpoint(maxpts)
real(8)    ls,lg,hon2,lon2,dx,dy,a0,da,plexp
real(8)    ym,nu
complex(8) z1,z2,z3
integer(4) cn(maxpts)
real(8)    angletangent(maxpts),anglenormal(maxpts)
real(8)    xinwnv(maxpts),yinwnv(maxpts)
real(8)    cangletangent(maxpts),canglenormal(maxpts)
real(8)    cxinwnv(maxpts),cyinwnv(maxpts)
integer(4) nsteps

filedbi = 'dogbone.dat'
filedbc = 'dogbone_cracked.in'
filedbu = 'dogbone_uncracked.in'

do i = 1,maxpts
  icrackpoint(i) = 0
enddo

open(lui,file=filedbi,status='OLD')
read(lui,*) ym,nu
read(lui,*) ls,lg
read(lui,*) ncracks,a0,nsteps,da,plexp,(icrackpoint(i),i=1,ncracks)
read(lui,*) nc
do i = 1,nc
  read(lui,*) cx(i),cy(i)
end do
close(lui)

if (cracked) then
  if (ncracks.le.0) then
    write(*,*) 'No cracks were defined. Proceeding to place a crack'
    write(*,*) 'at the first node on the line of symmetry.'
    ncracks = 1
    icrackpoint(1) = 1
  endif
  open(unit=luo,file=filedbc,status='REPLACE')
else
  ncracks = 0
  do i = 1,maxpts
    icrackpoint(i) = 0
  enddo
  open(unit=luo,file=filedbu,status='REPLACE')
```

```
endif

hon2 = cy(nc)
lon2 = ls/2.0d0

bx(01) = -cx(nc);  by(01) = +hon2
bx(02) = -lon2+lg; by(02) = +hon2
bx(03) = -lon2;    by(03) = +hon2
bx(04) = -lon2;    by(04) = 0.0d0
bx(05) = -lon2;    by(05) = -hon2
bx(06) = -lon2+lg; by(06) = -hon2
bx(07) = -cx(nc);  by(07) = -hon2
bx(08) = +cx(nc);  by(08) = -hon2
bx(09) = +lon2-lg; by(09) = -hon2
bx(10) = +lon2;    by(10) = -hon2
bx(11) = +lon2;    by(11) = 0.0d0
bx(12) = +lon2;    by(12) = +hon2
bx(13) = +lon2-lg; by(13) = +hon2
bx(14) = +cx(nc);  by(14) = +hon2

do i = 1,nc
  cn(i) = 0
enddo

do i = 1,ncracks
  cn(icrackpoint(i)) = i
enddo

call anglevector(nc,cx,cy,angletangent,anglenormal,xinwnv,yinwnv)

write(luo,'(a)') 'FADD2D input deck generated by CreateDogboneCouponModel'
write(luo,'(a)') 'Dogbone Fatigue Analysis Coupon'

if (cracked) then
  write(luo,'(a)') 'Edge cracked case'
else
  write(luo,'(a)') 'Uncracked case'
endif

call writedashedline(luo,ndash)
write(luo,'(a)') 'Problem Type, No of Materials'
write(luo,'(a)') '2 1'
write(luo,'(a)') 'Materials, Elastic modulus, and Poisson''s ratio'
write(luo,'(i1,f20.4,f17.4)') 1,ym,nu
write(luo,'(a)') 'Material, Cracks, Boundaries, and Point loads'

if (cracked) then
  write(luo,'(i1,i5.4,2i2)') 1,ncracks,1,0
  write(luo,'(a)') 'Crack-growth steps, increment, and Paris law exponent'
  write(luo,'(i4.4,2f12.4)') nsteps,da,plexp
else
  write(luo,'(a)') '1 0 1 0'
endif

write(luo,'(a)') 'Input echo, Boundary Stresses, and Displacements'
write(luo,'(a)') '1 1 1 1'
```

```
write(luo,'(a)') ''

if (cracked) then
  call writedashedline(luo,ndash)
  write(luo,'(a)') 'Definition of Crack'
  write(luo,'(a)') ''
  nelemcrack = 8
  do i = 1,ncracks
    write(luo,'(i4.4,i2)') i,1
    write(luo,'(a)') '   1 0 0 2 1'
    j = icrackpoint(i)
    if (mod(j,2) .eq. 0) then
      write(*,*)
      write(*,*) 'Error: Crack location index must be an odd number. Check your
input data.'
      write(*,*)
      stop
    endif
    dx = a0*xinwnv(j)
    dy = a0*yinwnv(j)
    write(luo,'(2i4,4f18.7,i6,f18.3)')
1,1,cx(j),cy(j),cx(j)+dx,cy(j)+dy,nelemcrack,anglenormal(j)
    write(luo,'(a)') ''
  enddo
endif

call writedashedline(luo,ndash)
write(luo,'(a)') 'Definition of Boundary'
write(luo,'(a)') ''
write(luo,'(a)') '1 1'
write(luo,'(i4.4,i2,i6)') ncracks,0,4*(nc/2)+nb-2

! Initialise counter that gets incremented when each
! boundary segment is created.

id = 0

! Write out the LH upper quadrant of the curved boundary.

nelem = 2
do i = 1,nc/2
  ic = (i-1)*2+1
  if (i.eq.1 .and. cn(1).gt.0) then
    call segpara(-cx(ic),+cy(ic),-cx(ic+1),+cy(ic+1),-cx(ic+2),+cy(ic+2), &
                 cn(ic),0,0,luo,id,8*nelem)
  else
    call segpara(-cx(ic),+cy(ic),-cx(ic+1),+cy(ic+1),-cx(ic+2),+cy(ic+2), &
                 0,0,0,luo,id,nelem)
  endif
enddo

! Write out next line segments.

nelem = 4
call segline(bx(01),by(01),bx(02),by(02),luo,id,nelem,-1,0.0d0,-1,0.0d0,3,0,1)
call segline(bx(02),by(02),bx(03),by(03),luo,id,nelem,-1,0.0d0,-1,0.0d0,1,0,1)
```

```
call segline(bx(03),by(03),bx(04),by(04),luo,id,nelem,-1, -px ,-1,0.0d0,3,1,1)
call segline(bx(04),by(04),bx(05),by(05),luo,id,nelem,-1, -px ,-1,0.0d0,1,1,1)
call segline(bx(05),by(05),bx(06),by(06),luo,id,nelem,-1,0.0d0,-1,0.0d0,3,0,1)
call segline(bx(06),by(06),bx(07),by(07),luo,id,nelem,-1,0.0d0,-1,0.0d0,1,0,1)

! Write out the LH lower quadrant of the curved boundary.

nelem = 1
do i = 1,nc/2
  ic = nc-(i-1)*2
  call segpara(-cx(ic),-cy(ic),-cx(ic-1),-cy(ic-1),-cx(ic-2),-cy(ic-2), &
               0,0,0,luo,id,nelem)
enddo

! Write out the RH lower quadrant of the curved boundary.

nelem = 1
do i = 1,nc/2
  ic = (i-1)*2+1
  call segpara(+cx(ic),-cy(ic),+cx(ic+1),-cy(ic+1),+cx(ic+2),-cy(ic+2), &
               0,0,0,luo,id,nelem)
enddo

! Write out next line segments.

nelem = 4
call segline(bx(08),by(08),bx(09),by(09),luo,id,nelem,-1,0.0d0,-1,0.0d0,3,0,1)
call segline(bx(09),by(09),bx(10),by(10),luo,id,nelem,-1,0.0d0,-1,0.0d0,1,0,1)
call segline(bx(10),by(10),bx(11),by(11),luo,id,nelem,-1, +px ,-1,0.0d0,3,0,1)
call segline(bx(11),by(11),bx(12),by(12),luo,id,nelem,-1, +px ,-1,0.0d0,1,0,1)
call segline(bx(12),by(12),bx(13),by(13),luo,id,nelem,-1,0.0d0,-1,0.0d0,3,0,1)
call segline(bx(13),by(13),bx(14),by(14),luo,id,nelem,-1,0.0d0,-1,0.0d0,1,0,1)

! Write out the RH upper quadrant of the curved boundary.

nelem = 2
do i = 1,nc/2
  ic = nc-(i-1)*2
  ! If a crack is located at either the start or end node of the
  ! parabolic segment, increase the mesh density for the segment.
  if (cn(ic).gt.0 .or. cn(ic-2).gt.0) then
    call segpara(+cx(ic),+cy(ic),+cx(ic-1),+cy(ic-1),+cx(ic-2),+cy(ic-2), &
                 cn(ic),cn(ic-1),cn(ic-2),luo,id,8*nelem)
  else
    call segpara(+cx(ic),+cy(ic),+cx(ic-1),+cy(ic-1),+cx(ic-2),+cy(ic-2), &
                 cn(ic),cn(ic-1),cn(ic-2),luo,id,nelem)
 endif
enddo

write(luo,'(a)') ' '
call writedashedline(luo,ndash)

close(luo)

end subroutine DogboneCouponModel
```

```
!================================================================================

subroutine writedashedline(luo,ndash)

implicit none

integer(4) luo,ndash,i

write(luo,'(2000a)') ('-',i=1,ndash)

end subroutine writedashedline

!================================================================================

subroutine segpara(x1,y1,x2,y2,x3,y3,cn1,cn2,cn3,luo,id,nelem)

implicit none

real(8)    x1,y1,x2,y2,x3,y3
integer(4) cn1,cn2,cn3
integer(4) luo,id,nelem

id = id + 1

write(luo,'(a)') ''
write(luo,'(i4.4,2i4)') id,1,nelem
write(luo,'(2f15.7,i4,f15.7,i4,f15.7,i4)') x1,y1,-1,0.0d0,-1,0.0d0,cn1
write(luo,'(2f15.7,i4,f15.7,i4,f15.7,i4)') x2,y2,-1,0.0d0,-1,0.0d0,cn2
write(luo,'(2f15.7,i4,f15.7,i4,f15.7,i4)') x3,y3,-1,0.0d0,-1,0.0d0,cn3

return

end subroutine segpara

!================================================================================

subroutine segline(x1,y1,x2,y2,luo,id,nelem,icx,vcx,icy,vcy,icn,icnx,icny)

implicit none

real(8)    x1,y1,x2,y2,vcx,vcy
integer(4) luo,id,nelem,icx,icy,icn,icnx,icny
real(8)    px
real(8)    xm,ym

id = id + 1

xm = (x1+x2)/2.0d0
ym = (y1+y2)/2.0d0

write(luo,'(a)') ''
write(luo,'(i4.4,2i4)') id,1,nelem
if (icn.eq.0) then
  write(luo,100) x1,y1,icx,vcx,icy,vcy,0
  write(luo,100) xm,ym,icx,vcx,icy,vcy,0
  write(luo,100) x2,y2,icx,vcx,icy,vcy,0
```

```
else
  if (icn.eq.1) then
    write(luo,100) x1,y1,icx,vcx,icy,vcy,-2,icnx,icny
  else
    write(luo,100) x1,y1,icx,vcx,icy,vcy,0
  end if
  if (icn.eq.2) then
    write(luo,100) xm,ym,icx,vcx,icy,vcy,-2,icnx,icny
  else
    write(luo,100) xm,ym,icx,vcx,icy,vcy,0
  end if
  if (icn.eq.3) then
    write(luo,100) x2,y2,icx,vcx,icy,vcy,-2,icnx,icny
  else
    write(luo,100) x2,y2,icx,vcx,icy,vcy,0
  end if
end if

return

100 format(2f15.7,i4,f15.7,i4,f15.7,3i4)

end subroutine segline

!==============================================================================

subroutine anglevector(n,xc,yc,angletangent,anglenormal,xinwnv,yinwnv)

! Determine the tangent angle, inward normal angle, and inward normal vector
! for points along the curved optimal boundary. It is assumed that the first
! point is mirrored about the y-axis.

implicit none

integer(4) n
real(8)    xc(n),yc(n),angletangent(n),anglenormal(n),xinwnv(n),yinwnv(n)
integer(4) i
real(8)    pi,pion2,twopi

pi    = 4.0d0*atan(1.0d0)
pion2 = pi/2.0d0
twopi = 2.0d0*pi

do i=1,n
  ! Compute angle of slope of the curve at each point on the curve.
  if (i.eq.1) then
    angletangent(i)=atan2(0.0d0,xc(i+1)-(-xc(i+1)))
  else if (i.eq.n) then
    angletangent(i)=atan2(yc(i)-yc(i-1),xc(i)-xc(i-1))
  else
    ! This simple formula for calculating the slope of the
    ! curve is equivalent to what is obtained by using
    ! a second-order Lagrange polynomial approximation.
    angletangent(i)=atan2(yc(i+1)-yc(i-1),xc(i+1)-xc(i-1))
  endif
  ! Compute angle of the outward normal.
```

```
  anglenormal(i)=angletangent(i)-pion2
  if (anglenormal(i).gt.pi) anglenormal(i)=anglenormal(i)-twopi
  ! Compute inward unit normal vector to boundary.
  xinwnv(i)=cos(anglenormal(i))
  yinwnv(i)=sin(anglenormal(i))
  ! Convert angles from radians to degrees.
  anglenormal(i)=anglenormal(i)*180.0d0/pi
  angletangent(i)=angletangent(i)*180.0d0/pi
enddo

return
end

!==============================================================================

subroutine circle(x1,y1,x2,y2,x3,y3,xc,yc,r,det)

! Determine the centre coordinates (xc,yc) and radius r of a circle passing
! through three points, (x1,y1) (x2,y2) (x3,y3).
!
! If the value of det is zero, then a circle through the three given points
! does not exist. e.g. the three points are colinear.

implicit none

real*8 x1,y1,x2,y2,x3,y3,xc,yc,r,det

real*8 a1,a2,c1,c2,b1,b2

a1=2.0*(x2-x1)
a2=2.0*(x3-x2)
b1=2.0*(y2-y1)
b2=2.0*(y3-y2)
c1=x2**2+y2**2-x1**2-y1**2
c2=x3**2+y3**2-x2**2-y2**2

det=a1*b2-b1*a2

if (det.ne.0.0) then
  xc=(c1*b2-b1*c2)/det
  yc=(a1*c2-c1*a2)/det
  a1=xc-x1
  a2=yc-y1
  r=dsqrt(a1**2+a2**2)
else
  xc=0.0d0
  yc=0.0d0
  r=0.0d0
endif

return
end

!==============================================================================

subroutine canglevector(n,xc,yc,angletangent,anglenormal,xinwnv,yinwnv)
```

```
! Determine the tangent angle, inward normal angle, and inward normal vector
! for points along the curved optimal boundary. It is assumed that the first
! point is mirrored about the y-axis.

implicit none

integer(4) n
real(8)    xc(n),yc(n),angletangent(n),anglenormal(n),xinwnv(n),yinwnv(n)
integer(4) i
real(8)    pi,pion2,twopi,r,cx,cy,det

pi    = 4.0d0*atan(1.0d0)
pion2 = pi/2.0d0
twopi = 2.0d0*pi

do i=1,n
  ! Compute angle of slope of the curve at each point on the curve.
  if (i.eq.1) then
    call circle(-xc(i+1),yc(i+1),xc(i),yc(i),xc(i+1),yc(i+1),cx,cy,r,det)
    if (det.eq.0.0d0) then
      angletangent(i)=atan2(0.0d0,xc(i+1)-(-xc(i+1)))
    endif
  else if (i.eq.n) then
    call circle(xc(i-2),yc(i-2),xc(i-1),yc(i-1),xc(i),yc(i),cx,cy,r,det)
    if (det.eq.0.0d0) then
      angletangent(i)=atan2(yc(i)-yc(i-1),xc(i)-xc(i-1))
    endif
  else
    call circle(xc(i-1),yc(i-1),xc(i),yc(i),xc(i+1),yc(i+1),cx,cy,r,det)
    if (det.eq.0.0d0) then
      angletangent(i)=atan2(yc(i+1)-yc(i-1),xc(i+1)-xc(i-1))
    endif
  endif
  ! Compute angle of the outward normal.
  if (det.eq.0.0d0) then
    anglenormal(i)=angletangent(i)-pion2
  else
    anglenormal(i) = atan2(yc(i)-cy,xc(i)-cx)
    angletangent(i) = anglenormal(i)+pion2
  endif
  if (anglenormal(i).gt.pi) anglenormal(i)=anglenormal(i)-twopi
  ! Compute inward unit normal vector to boundary.
  xinwnv(i)=cos(anglenormal(i))
  yinwnv(i)=sin(anglenormal(i))
  ! Convert angles from radians to degrees.
  anglenormal(i)=anglenormal(i)*180.0d0/pi
  angletangent(i)=angletangent(i)*180.0d0/pi
enddo

return
end
```

Appendix E:

Input deck used to create FADD2D model of original constant-stress coupon using CreateDogboneCouponModel program

The following input file can also be found stored in Objective folder fAV1044714.

```
72400.0 0.33
160.0 40.0
1 0.10 199 0.10 3.0 1
37
   0.000000       12.500000
   1.040013       12.502718
   2.096924       12.510549
   3.153789       12.523134
   4.210584       12.540315
   5.267295       12.562121
   6.323909       12.588742
   7.380377       12.620489
   8.436671       12.657774
   9.492742       12.700915
  10.548531       12.750359
  11.603993       12.806458
  12.659052       12.869623
  13.713637       12.940341
  14.767647       13.019109
  15.820983       13.106494
  16.873507       13.203122
  17.925085       13.309665
  18.975613       13.426894
  20.024801       13.555622
  21.072376       13.696856
  22.118006       13.851865
  23.161242       14.022339
  24.201506       14.210653
  25.237661       14.420102
  26.268244       14.655024
  27.290857       14.921516
  28.302109       15.226401
  29.297739       15.579076
  30.271200       15.988238
  31.212088       16.463631
  32.102810       17.007961
  32.937607       17.631344
  33.710354       18.341629
  34.400757       19.132950
  34.700379       19.566475
  35.000000       20.000000
```

Appendix F:

FADD2D input file for Modified Constant-Stress Coupon with one centrally-located through-thickness edge crack

The following input file can also be found stored in Objective folder fAV1044714.

```
FADD2D input deck generated by CreateDogboneCouponModel
Dog-bone Fatigue Analysis Coupon
Edge cracked case
--------------------------------------------------------------------------------------
Problem Type, No of Materials
2 1
Materials, Elastic modulus, and Poisson's ratio
1          72400.0000          0.3000
Material, Cracks, Boundaries, and Point loads
1 0001 1 0
Crack-growth steps, increment, and Paris law exponent
0199      0.1000      3.0000
Input echo, Boundary Stresses, and Displacements
1 1 1 1

--------------------------------------------------------------------------------------
Definition of Crack

0001 1
   1 0 0 2 1
   1   1    0.0000000    12.5000000     0.0000000    12.4000000     8        -90.000

--------------------------------------------------------------------------------------
Definition of Boundary

1 1
0001 0   172

0001   1  16
      0.0000000     12.5000000  -1      0.0000000  -1      0.0000000   1
     -0.5269560     12.5009750  -1      0.0000000  -1      0.0000000   0
     -1.0548970     12.5038980  -1      0.0000000  -1      0.0000000   0

0002   1   2
     -1.0548970     12.5038980  -1      0.0000000  -1      0.0000000   0
     -1.5831520     12.5087610  -1      0.0000000  -1      0.0000000   0
     -2.1121110     12.5155840  -1      0.0000000  -1      0.0000000   0

0003   1   2
     -2.1121110     12.5155840  -1      0.0000000  -1      0.0000000   0
     -2.6419170     12.5243890  -1      0.0000000  -1      0.0000000   0
     -3.1729650     12.5352090  -1      0.0000000  -1      0.0000000   0

0004   1   2
     -3.1729650     12.5352090  -1      0.0000000  -1      0.0000000   0
     -3.7053990     12.5481030  -1      0.0000000  -1      0.0000000   0
     -4.2397240     12.5631460  -1      0.0000000  -1      0.0000000   0
```

```
0005   1   2
     -4.2397240     12.5631460  -1      0.0000000  -1      0.0000000   0
     -4.7759650     12.5803830  -1      0.0000000  -1      0.0000000   0
     -5.3146670     12.5998890  -1      0.0000000  -1      0.0000000   0

0006   1   2
     -5.3146670     12.5998890  -1      0.0000000  -1      0.0000000   0
     -5.8545820     12.6217180  -1      0.0000000  -1      0.0000000   0
     -6.3876870     12.6455960  -1      0.0000000  -1      0.0000000   0

0007   1   2
     -6.3876870     12.6455960  -1      0.0000000  -1      0.0000000   0
     -6.9200650     12.6717650  -1      0.0000000  -1      0.0000000   0
     -7.4515850     12.7002270  -1      0.0000000  -1      0.0000000   0

0008   1   2
     -7.4515850     12.7002270  -1      0.0000000  -1      0.0000000   0
     -7.9827010     12.7310960  -1      0.0000000  -1      0.0000000   0
     -8.5133160     12.7644570  -1      0.0000000  -1      0.0000000   0

0009   1   2
     -8.5133160     12.7644570  -1      0.0000000  -1      0.0000000   0
     -9.0435910     12.8003850  -1      0.0000000  -1      0.0000000   0
     -9.5734790     12.8389350  -1      0.0000000  -1      0.0000000   0

0010   1   2
     -9.5734790     12.8389350  -1      0.0000000  -1      0.0000000   0
    -10.1029990     12.8802070  -1      0.0000000  -1      0.0000000   0
    -10.6321650     12.9243020  -1      0.0000000  -1      0.0000000   0

0011   1   2
    -10.6321650     12.9243020  -1      0.0000000  -1      0.0000000   0
    -11.1609440     12.9712940  -1      0.0000000  -1      0.0000000   0
    -11.6893620     13.0212660  -1      0.0000000  -1      0.0000000   0

0012   1   2
    -11.6893620     13.0212660  -1      0.0000000  -1      0.0000000   0
    -12.2173350     13.0743260  -1      0.0000000  -1      0.0000000   0
    -12.7449000     13.1306100  -1      0.0000000  -1      0.0000000   0

0013   1   2
    -12.7449000     13.1306100  -1      0.0000000  -1      0.0000000   0
    -13.2720240     13.1902110  -1      0.0000000  -1      0.0000000   0
    -13.7986800     13.2532360  -1      0.0000000  -1      0.0000000   0

0014   1   2
    -13.7986800     13.2532360  -1      0.0000000  -1      0.0000000   0
    -14.3248320     13.3197950  -1      0.0000000  -1      0.0000000   0
    -14.8504690     13.3900040  -1      0.0000000  -1      0.0000000   0

0015   1   2
    -14.8504690     13.3900040  -1      0.0000000  -1      0.0000000   0
    -15.3755720     13.4640060  -1      0.0000000  -1      0.0000000   0
    -15.9001150     13.5419440  -1      0.0000000  -1      0.0000000   0

0016   1   2
    -15.9001150     13.5419440  -1      0.0000000  -1      0.0000000   0
    -16.4240060     13.6239530  -1      0.0000000  -1      0.0000000   0
    -16.9472920     13.7101910  -1      0.0000000  -1      0.0000000   0

0017   1   2
    -16.9472920     13.7101910  -1      0.0000000  -1      0.0000000   0
```

```
    -17.4698810     13.8008030  -1      0.0000000  -1      0.0000000   0
    -17.9918290     13.8959670  -1      0.0000000  -1      0.0000000   0

0018   1   2
    -17.9918290     13.8959670  -1      0.0000000  -1      0.0000000   0
    -18.5130540     13.9958890  -1      0.0000000  -1      0.0000000   0
    -19.0334590     14.1008050  -1      0.0000000  -1      0.0000000   0

0019   1   2
    -19.0334590     14.1008050  -1      0.0000000  -1      0.0000000   0
    -19.5530890     14.2109080  -1      0.0000000  -1      0.0000000   0
    -20.0719290     14.3264120  -1      0.0000000  -1      0.0000000   0

0020   1   2
    -20.0719290     14.3264120  -1      0.0000000  -1      0.0000000   0
    -20.5900300     14.4476180  -1      0.0000000  -1      0.0000000   0
    -21.1072320     14.5748160  -1      0.0000000  -1      0.0000000   0

0021   1   2
    -21.1072320     14.5748160  -1      0.0000000  -1      0.0000000   0
    -21.6237560     14.7084000  -1      0.0000000  -1      0.0000000   0
    -22.1392270     14.8486600  -1      0.0000000  -1      0.0000000   0

0022   1   2
    -22.1392270     14.8486600  -1      0.0000000  -1      0.0000000   0
    -22.6541940     14.9961780  -1      0.0000000  -1      0.0000000   0
    -23.1680960     15.1513480  -1      0.0000000  -1      0.0000000   0

0023   1   2
    -23.1680960     15.1513480  -1      0.0000000  -1      0.0000000   0
    -23.6814600     15.3152570  -1      0.0000000  -1      0.0000000   0
    -24.1937660     15.4889750  -1      0.0000000  -1      0.0000000   0

0024   1   2
    -24.1937660     15.4889750  -1      0.0000000  -1      0.0000000   0
    -24.7067210     15.6738580  -1      0.0000000  -1      0.0000000   0
    -25.2644210     15.8886490  -1      0.0000000  -1      0.0000000   0

0025   1   2
    -25.2644210     15.8886490  -1      0.0000000  -1      0.0000000   0
    -25.8168760     16.1193410  -1      0.0000000  -1      0.0000000   0
    -26.3618170     16.3672470  -1      0.0000000  -1      0.0000000   0

0026   1   2
    -26.3618170     16.3672470  -1      0.0000000  -1      0.0000000   0
    -26.8985910     16.6322690  -1      0.0000000  -1      0.0000000   0
    -27.4269430     16.9135610  -1      0.0000000  -1      0.0000000   0

0027   1   2
    -27.4269430     16.9135610  -1      0.0000000  -1      0.0000000   0
    -27.9463980     17.2108080  -1      0.0000000  -1      0.0000000   0
    -28.4564090     17.5238130  -1      0.0000000  -1      0.0000000   0

0028   1   2
    -28.4564090     17.5238130  -1      0.0000000  -1      0.0000000   0
    -28.9564640     17.8523280  -1      0.0000000  -1      0.0000000   0
    -29.4460510     18.1960790  -1      0.0000000  -1      0.0000000   0

0029   1   2
    -29.4460510     18.1960790  -1      0.0000000  -1      0.0000000   0
    -29.9246720     18.5547780  -1      0.0000000  -1      0.0000000   0
    -30.3918430     18.9281140  -1      0.0000000  -1      0.0000000   0
```

```
0030   1   2
    -30.3918430     18.9281140  -1      0.0000000  -1      0.0000000   0
    -30.8470810     19.3157570  -1      0.0000000  -1      0.0000000   0
    -31.2899290     19.7173620  -1      0.0000000  -1      0.0000000   0

0031   1   2
    -31.2899290     19.7173620  -1      0.0000000  -1      0.0000000   0
    -31.7199390     20.1325620  -1      0.0000000  -1      0.0000000   0
    -32.1366780     20.5609680  -1      0.0000000  -1      0.0000000   0

0032   1   2
    -32.1366780     20.5609680  -1      0.0000000  -1      0.0000000   0
    -32.5397330     21.0021790  -1      0.0000000  -1      0.0000000   0
    -32.9287130     21.4557740  -1      0.0000000  -1      0.0000000   0

0033   1   2
    -32.9287130     21.4557740  -1      0.0000000  -1      0.0000000   0
    -33.3032360     21.9213120  -1      0.0000000  -1      0.0000000   0
    -33.6629540     22.3983410  -1      0.0000000  -1      0.0000000   0

0034   1   2
    -33.6629540     22.3983410  -1      0.0000000  -1      0.0000000   0
    -34.0075320     22.8863920  -1      0.0000000  -1      0.0000000   0
    -34.3366610     23.3849790  -1      0.0000000  -1      0.0000000   0

0035   1   2
    -34.3366610     23.3849790  -1      0.0000000  -1      0.0000000   0
    -34.6500560     23.8936100  -1      0.0000000  -1      0.0000000   0
    -34.9474520     24.4117710  -1      0.0000000  -1      0.0000000   0

0036   1   2
    -34.9474520     24.4117710  -1      0.0000000  -1      0.0000000   0
    -35.2286050     24.9389450  -1      0.0000000  -1      0.0000000   0
    -35.4933050     25.4746060  -1      0.0000000  -1      0.0000000   0

0037   1   2
    -35.4933050     25.4746060  -1      0.0000000  -1      0.0000000   0
    -35.7413540     26.0182160  -1      0.0000000  -1      0.0000000   0
    -35.9725840     26.5692330  -1      0.0000000  -1      0.0000000   0

0038   1   2
    -35.9725840     26.5692330  -1      0.0000000  -1      0.0000000   0
    -36.1868470     27.1271100  -1      0.0000000  -1      0.0000000   0
    -36.3840200     27.6912950  -1      0.0000000  -1      0.0000000   0

0039   1   2
    -36.3840200     27.6912950  -1      0.0000000  -1      0.0000000   0
    -36.5639950     28.2612320  -1      0.0000000  -1      0.0000000   0
    -36.7266910     28.8363660  -1      0.0000000  -1      0.0000000   0

0040   1   2
    -36.7266910     28.8363660  -1      0.0000000  -1      0.0000000   0
    -36.8720530     29.4161390  -1      0.0000000  -1      0.0000000   0
    -37.0000000     30.0000000  -1      0.0000000  -1      0.0000000   0

0041   1   4
    -37.0000000     30.0000000  -1      0.0000000  -1      0.0000000   0
    -49.5000000     30.0000000  -1      0.0000000  -1      0.0000000   0
    -62.0000000     30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1

0042   1   4
```

```
    -62.0000000    30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1
    -92.0000000    30.0000000  -1      0.0000000  -1      0.0000000   0
   -122.0000000    30.0000000  -1      0.0000000  -1      0.0000000   0

0043   1   4
   -122.0000000    30.0000000  -1   -100.0000000  -1      0.0000000   0
   -122.0000000    15.0000000  -1   -100.0000000  -1      0.0000000   0
   -122.0000000     0.0000000  -1   -100.0000000  -1      0.0000000  -2   1   1

0044   1   4
   -122.0000000     0.0000000  -1   -100.0000000  -1      0.0000000  -2   1   1
   -122.0000000   -15.0000000  -1   -100.0000000  -1      0.0000000   0
   -122.0000000   -30.0000000  -1   -100.0000000  -1      0.0000000   0

0045   1   4
   -122.0000000   -30.0000000  -1      0.0000000  -1      0.0000000   0
    -92.0000000   -30.0000000  -1      0.0000000  -1      0.0000000   0
    -62.0000000   -30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1

0046   1   4
    -62.0000000   -30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1
    -49.5000000   -30.0000000  -1      0.0000000  -1      0.0000000   0
    -37.0000000   -30.0000000  -1      0.0000000  -1      0.0000000   0

0047   1   1
    -37.0000000   -30.0000000  -1      0.0000000  -1      0.0000000   0
    -36.8720530   -29.4161390  -1      0.0000000  -1      0.0000000   0
    -36.7266910   -28.8363660  -1      0.0000000  -1      0.0000000   0

0048   1   1
    -36.7266910   -28.8363660  -1      0.0000000  -1      0.0000000   0
    -36.5639950   -28.2612320  -1      0.0000000  -1      0.0000000   0
    -36.3840200   -27.6912950  -1      0.0000000  -1      0.0000000   0

0049   1   1
    -36.3840200   -27.6912950  -1      0.0000000  -1      0.0000000   0
    -36.1868470   -27.1271100  -1      0.0000000  -1      0.0000000   0
    -35.9725840   -26.5692330  -1      0.0000000  -1      0.0000000   0

0050   1   1
    -35.9725840   -26.5692330  -1      0.0000000  -1      0.0000000   0
    -35.7413540   -26.0182160  -1      0.0000000  -1      0.0000000   0
    -35.4933050   -25.4746060  -1      0.0000000  -1      0.0000000   0

0051   1   1
    -35.4933050   -25.4746060  -1      0.0000000  -1      0.0000000   0
    -35.2286050   -24.9389450  -1      0.0000000  -1      0.0000000   0
    -34.9474520   -24.4117710  -1      0.0000000  -1      0.0000000   0

0052   1   1
    -34.9474520   -24.4117710  -1      0.0000000  -1      0.0000000   0
    -34.6500560   -23.8936100  -1      0.0000000  -1      0.0000000   0
    -34.3366610   -23.3849790  -1      0.0000000  -1      0.0000000   0

0053   1   1
    -34.3366610   -23.3849790  -1      0.0000000  -1      0.0000000   0
    -34.0075320   -22.8863920  -1      0.0000000  -1      0.0000000   0
    -33.6629540   -22.3983410  -1      0.0000000  -1      0.0000000   0

0054   1   1
    -33.6629540   -22.3983410  -1      0.0000000  -1      0.0000000   0
    -33.3032360   -21.9213120  -1      0.0000000  -1      0.0000000   0
```

```
    -32.9287130    -21.4557740  -1      0.0000000  -1      0.0000000   0

0055   1   1
    -32.9287130    -21.4557740  -1      0.0000000  -1      0.0000000   0
    -32.5397330    -21.0021790  -1      0.0000000  -1      0.0000000   0
    -32.1366780    -20.5609680  -1      0.0000000  -1      0.0000000   0

0056   1   1
    -32.1366780    -20.5609680  -1      0.0000000  -1      0.0000000   0
    -31.7199390    -20.1325620  -1      0.0000000  -1      0.0000000   0
    -31.2899290    -19.7173620  -1      0.0000000  -1      0.0000000   0

0057   1   1
    -31.2899290    -19.7173620  -1      0.0000000  -1      0.0000000   0
    -30.8470810    -19.3157570  -1      0.0000000  -1      0.0000000   0
    -30.3918430    -18.9281140  -1      0.0000000  -1      0.0000000   0

0058   1   1
    -30.3918430    -18.9281140  -1      0.0000000  -1      0.0000000   0
    -29.9246720    -18.5547780  -1      0.0000000  -1      0.0000000   0
    -29.4460510    -18.1960790  -1      0.0000000  -1      0.0000000   0

0059   1   1
    -29.4460510    -18.1960790  -1      0.0000000  -1      0.0000000   0
    -28.9564640    -17.8523280  -1      0.0000000  -1      0.0000000   0
    -28.4564090    -17.5238130  -1      0.0000000  -1      0.0000000   0

0060   1   1
    -28.4564090    -17.5238130  -1      0.0000000  -1      0.0000000   0
    -27.9463980    -17.2108080  -1      0.0000000  -1      0.0000000   0
    -27.4269430    -16.9135610  -1      0.0000000  -1      0.0000000   0

0061   1   1
    -27.4269430    -16.9135610  -1      0.0000000  -1      0.0000000   0
    -26.8985910    -16.6322690  -1      0.0000000  -1      0.0000000   0
    -26.3618170    -16.3672470  -1      0.0000000  -1      0.0000000   0

0062   1   1
    -26.3618170    -16.3672470  -1      0.0000000  -1      0.0000000   0
    -25.8168760    -16.1193410  -1      0.0000000  -1      0.0000000   0
    -25.2644210    -15.8886490  -1      0.0000000  -1      0.0000000   0

0063   1   1
    -25.2644210    -15.8886490  -1      0.0000000  -1      0.0000000   0
    -24.7067210    -15.6738580  -1      0.0000000  -1      0.0000000   0
    -24.1937660    -15.4889750  -1      0.0000000  -1      0.0000000   0

0064   1   1
    -24.1937660    -15.4889750  -1      0.0000000  -1      0.0000000   0
    -23.6814600    -15.3152570  -1      0.0000000  -1      0.0000000   0
    -23.1680960    -15.1513480  -1      0.0000000  -1      0.0000000   0

0065   1   1
    -23.1680960    -15.1513480  -1      0.0000000  -1      0.0000000   0
    -22.6541940    -14.9961780  -1      0.0000000  -1      0.0000000   0
    -22.1392270    -14.8486600  -1      0.0000000  -1      0.0000000   0

0066   1   1
    -22.1392270    -14.8486600  -1      0.0000000  -1      0.0000000   0
    -21.6237560    -14.7084000  -1      0.0000000  -1      0.0000000   0
    -21.1072320    -14.5748160  -1      0.0000000  -1      0.0000000   0
```

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0067   1   1
    -21.1072320    -14.5748160  -1      0.0000000  -1      0.0000000   0
    -20.5900300    -14.4476180  -1      0.0000000  -1      0.0000000   0
    -20.0719290    -14.3264120  -1      0.0000000  -1      0.0000000   0

0068   1   1
    -20.0719290    -14.3264120  -1      0.0000000  -1      0.0000000   0
    -19.5530890    -14.2109080  -1      0.0000000  -1      0.0000000   0
    -19.0334590    -14.1008050  -1      0.0000000  -1      0.0000000   0

0069   1   1
    -19.0334590    -14.1008050  -1      0.0000000  -1      0.0000000   0
    -18.5130540    -13.9958890  -1      0.0000000  -1      0.0000000   0
    -17.9918290    -13.8959670  -1      0.0000000  -1      0.0000000   0

0070   1   1
    -17.9918290    -13.8959670  -1      0.0000000  -1      0.0000000   0
    -17.4698810    -13.8008030  -1      0.0000000  -1      0.0000000   0
    -16.9472920    -13.7101910  -1      0.0000000  -1      0.0000000   0

0071   1   1
    -16.9472920    -13.7101910  -1      0.0000000  -1      0.0000000   0
    -16.4240060    -13.6239530  -1      0.0000000  -1      0.0000000   0
    -15.9001150    -13.5419440  -1      0.0000000  -1      0.0000000   0

0072   1   1
    -15.9001150    -13.5419440  -1      0.0000000  -1      0.0000000   0
    -15.3755720    -13.4640060  -1      0.0000000  -1      0.0000000   0
    -14.8504690    -13.3900040  -1      0.0000000  -1      0.0000000   0

0073   1   1
    -14.8504690    -13.3900040  -1      0.0000000  -1      0.0000000   0
    -14.3248320    -13.3197950  -1      0.0000000  -1      0.0000000   0
    -13.7986800    -13.2532360  -1      0.0000000  -1      0.0000000   0

0074   1   1
    -13.7986800    -13.2532360  -1      0.0000000  -1      0.0000000   0
    -13.2720240    -13.1902110  -1      0.0000000  -1      0.0000000   0
    -12.7449000    -13.1306100  -1      0.0000000  -1      0.0000000   0

0075   1   1
    -12.7449000    -13.1306100  -1      0.0000000  -1      0.0000000   0
    -12.2173350    -13.0743260  -1      0.0000000  -1      0.0000000   0
    -11.6893620    -13.0212660  -1      0.0000000  -1      0.0000000   0

0076   1   1
    -11.6893620    -13.0212660  -1      0.0000000  -1      0.0000000   0
    -11.1609440    -12.9712940  -1      0.0000000  -1      0.0000000   0
    -10.6321650    -12.9243020  -1      0.0000000  -1      0.0000000   0

0077   1   1
    -10.6321650    -12.9243020  -1      0.0000000  -1      0.0000000   0
    -10.1029990    -12.8802070  -1      0.0000000  -1      0.0000000   0
     -9.5734790    -12.8389350  -1      0.0000000  -1      0.0000000   0

0078   1   1
     -9.5734790    -12.8389350  -1      0.0000000  -1      0.0000000   0
     -9.0435910    -12.8003850  -1      0.0000000  -1      0.0000000   0
     -8.5133160    -12.7644570  -1      0.0000000  -1      0.0000000   0

0079   1   1
     -8.5133160    -12.7644570  -1      0.0000000  -1      0.0000000   0
```

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     -7.9827010    -12.7310960  -1       0.0000000  -1       0.0000000   0
     -7.4515850    -12.7002270  -1       0.0000000  -1       0.0000000   0

0080   1   1
     -7.4515850    -12.7002270  -1       0.0000000  -1       0.0000000   0
     -6.9200650    -12.6717650  -1       0.0000000  -1       0.0000000   0
     -6.3876870    -12.6455960  -1       0.0000000  -1       0.0000000   0

0081   1   1
     -6.3876870    -12.6455960  -1       0.0000000  -1       0.0000000   0
     -5.8545820    -12.6217180  -1       0.0000000  -1       0.0000000   0
     -5.3146670    -12.5998890  -1       0.0000000  -1       0.0000000   0

0082   1   1
     -5.3146670    -12.5998890  -1       0.0000000  -1       0.0000000   0
     -4.7759650    -12.5803830  -1       0.0000000  -1       0.0000000   0
     -4.2397240    -12.5631460  -1       0.0000000  -1       0.0000000   0

0083   1   1
     -4.2397240    -12.5631460  -1       0.0000000  -1       0.0000000   0
     -3.7053990    -12.5481030  -1       0.0000000  -1       0.0000000   0
     -3.1729650    -12.5352090  -1       0.0000000  -1       0.0000000   0

0084   1   1
     -3.1729650    -12.5352090  -1       0.0000000  -1       0.0000000   0
     -2.6419170    -12.5243890  -1       0.0000000  -1       0.0000000   0
     -2.1121110    -12.5155840  -1       0.0000000  -1       0.0000000   0

0085   1   1
     -2.1121110    -12.5155840  -1       0.0000000  -1       0.0000000   0
     -1.5831520    -12.5087610  -1       0.0000000  -1       0.0000000   0
     -1.0548970    -12.5038980  -1       0.0000000  -1       0.0000000   0

0086   1   1
     -1.0548970    -12.5038980  -1       0.0000000  -1       0.0000000   0
     -0.5269560    -12.5009750  -1       0.0000000  -1       0.0000000   0
      0.0000000    -12.5000000  -1       0.0000000  -1       0.0000000   0

0087   1   1
      0.0000000    -12.5000000  -1       0.0000000  -1       0.0000000   0
      0.5269560    -12.5009750  -1       0.0000000  -1       0.0000000   0
      1.0548970    -12.5038980  -1       0.0000000  -1       0.0000000   0

0088   1   1
      1.0548970    -12.5038980  -1       0.0000000  -1       0.0000000   0
      1.5831520    -12.5087610  -1       0.0000000  -1       0.0000000   0
      2.1121110    -12.5155840  -1       0.0000000  -1       0.0000000   0

0089   1   1
      2.1121110    -12.5155840  -1       0.0000000  -1       0.0000000   0
      2.6419170    -12.5243890  -1       0.0000000  -1       0.0000000   0
      3.1729650    -12.5352090  -1       0.0000000  -1       0.0000000   0

0090   1   1
      3.1729650    -12.5352090  -1       0.0000000  -1       0.0000000   0
      3.7053990    -12.5481030  -1       0.0000000  -1       0.0000000   0
      4.2397240    -12.5631460  -1       0.0000000  -1       0.0000000   0

0091   1   1
      4.2397240    -12.5631460  -1       0.0000000  -1       0.0000000   0
      4.7759650    -12.5803830  -1       0.0000000  -1       0.0000000   0
      5.3146670    -12.5998890  -1       0.0000000  -1       0.0000000   0
```

```
0092   1   1
      5.3146670    -12.5998890  -1       0.0000000  -1       0.0000000   0
      5.8545820    -12.6217180  -1       0.0000000  -1       0.0000000   0
      6.3876870    -12.6455960  -1       0.0000000  -1       0.0000000   0

0093   1   1
      6.3876870    -12.6455960  -1       0.0000000  -1       0.0000000   0
      6.9200650    -12.6717650  -1       0.0000000  -1       0.0000000   0
      7.4515850    -12.7002270  -1       0.0000000  -1       0.0000000   0

0094   1   1
      7.4515850    -12.7002270  -1       0.0000000  -1       0.0000000   0
      7.9827010    -12.7310960  -1       0.0000000  -1       0.0000000   0
      8.5133160    -12.7644570  -1       0.0000000  -1       0.0000000   0

0095   1   1
      8.5133160    -12.7644570  -1       0.0000000  -1       0.0000000   0
      9.0435910    -12.8003850  -1       0.0000000  -1       0.0000000   0
      9.5734790    -12.8389350  -1       0.0000000  -1       0.0000000   0

0096   1   1
      9.5734790    -12.8389350  -1       0.0000000  -1       0.0000000   0
     10.1029990    -12.8802070  -1       0.0000000  -1       0.0000000   0
     10.6321650    -12.9243020  -1       0.0000000  -1       0.0000000   0

0097   1   1
     10.6321650    -12.9243020  -1       0.0000000  -1       0.0000000   0
     11.1609440    -12.9712940  -1       0.0000000  -1       0.0000000   0
     11.6893620    -13.0212660  -1       0.0000000  -1       0.0000000   0

0098   1   1
     11.6893620    -13.0212660  -1       0.0000000  -1       0.0000000   0
     12.2173350    -13.0743260  -1       0.0000000  -1       0.0000000   0
     12.7449000    -13.1306100  -1       0.0000000  -1       0.0000000   0

0099   1   1
     12.7449000    -13.1306100  -1       0.0000000  -1       0.0000000   0
     13.2720240    -13.1902110  -1       0.0000000  -1       0.0000000   0
     13.7986800    -13.2532360  -1       0.0000000  -1       0.0000000   0

0100   1   1
     13.7986800    -13.2532360  -1       0.0000000  -1       0.0000000   0
     14.3248320    -13.3197950  -1       0.0000000  -1       0.0000000   0
     14.8504690    -13.3900040  -1       0.0000000  -1       0.0000000   0

0101   1   1
     14.8504690    -13.3900040  -1       0.0000000  -1       0.0000000   0
     15.3755720    -13.4640060  -1       0.0000000  -1       0.0000000   0
     15.9001150    -13.5419440  -1       0.0000000  -1       0.0000000   0

0102   1   1
     15.9001150    -13.5419440  -1       0.0000000  -1       0.0000000   0
     16.4240060    -13.6239530  -1       0.0000000  -1       0.0000000   0
     16.9472920    -13.7101910  -1       0.0000000  -1       0.0000000   0

0103   1   1
     16.9472920    -13.7101910  -1       0.0000000  -1       0.0000000   0
     17.4698810    -13.8008030  -1       0.0000000  -1       0.0000000   0
     17.9918290    -13.8959670  -1       0.0000000  -1       0.0000000   0

0104   1   1
```

```
          17.9918290     -13.8959670   -1        0.0000000   -1        0.0000000    0
          18.5130540     -13.9958890   -1        0.0000000   -1        0.0000000    0
          19.0334590     -14.1008050   -1        0.0000000   -1        0.0000000    0

0105    1    1
          19.0334590     -14.1008050   -1        0.0000000   -1        0.0000000    0
          19.5530890     -14.2109080   -1        0.0000000   -1        0.0000000    0
          20.0719290     -14.3264120   -1        0.0000000   -1        0.0000000    0

0106    1    1
          20.0719290     -14.3264120   -1        0.0000000   -1        0.0000000    0
          20.5900300     -14.4476180   -1        0.0000000   -1        0.0000000    0
          21.1072320     -14.5748160   -1        0.0000000   -1        0.0000000    0

0107    1    1
          21.1072320     -14.5748160   -1        0.0000000   -1        0.0000000    0
          21.6237560     -14.7084000   -1        0.0000000   -1        0.0000000    0
          22.1392270     -14.8486600   -1        0.0000000   -1        0.0000000    0

0108    1    1
          22.1392270     -14.8486600   -1        0.0000000   -1        0.0000000    0
          22.6541940     -14.9961780   -1        0.0000000   -1        0.0000000    0
          23.1680960     -15.1513480   -1        0.0000000   -1        0.0000000    0

0109    1    1
          23.1680960     -15.1513480   -1        0.0000000   -1        0.0000000    0
          23.6814600     -15.3152570   -1        0.0000000   -1        0.0000000    0
          24.1937660     -15.4889750   -1        0.0000000   -1        0.0000000    0

0110    1    1
          24.1937660     -15.4889750   -1        0.0000000   -1        0.0000000    0
          24.7067210     -15.6738580   -1        0.0000000   -1        0.0000000    0
          25.2644210     -15.8886490   -1        0.0000000   -1        0.0000000    0

0111    1    1
          25.2644210     -15.8886490   -1        0.0000000   -1        0.0000000    0
          25.8168760     -16.1193410   -1        0.0000000   -1        0.0000000    0
          26.3618170     -16.3672470   -1        0.0000000   -1        0.0000000    0

0112    1    1
          26.3618170     -16.3672470   -1        0.0000000   -1        0.0000000    0
          26.8985910     -16.6322690   -1        0.0000000   -1        0.0000000    0
          27.4269430     -16.9135610   -1        0.0000000   -1        0.0000000    0

0113    1    1
          27.4269430     -16.9135610   -1        0.0000000   -1        0.0000000    0
          27.9463980     -17.2108080   -1        0.0000000   -1        0.0000000    0
          28.4564090     -17.5238130   -1        0.0000000   -1        0.0000000    0

0114    1    1
          28.4564090     -17.5238130   -1        0.0000000   -1        0.0000000    0
          28.9564640     -17.8523280   -1        0.0000000   -1        0.0000000    0
          29.4460510     -18.1960790   -1        0.0000000   -1        0.0000000    0

0115    1    1
          29.4460510     -18.1960790   -1        0.0000000   -1        0.0000000    0
          29.9246720     -18.5547780   -1        0.0000000   -1        0.0000000    0
          30.3918430     -18.9281140   -1        0.0000000   -1        0.0000000    0

0116    1    1
          30.3918430     -18.9281140   -1        0.0000000   -1        0.0000000    0
          30.8470810     -19.3157570   -1        0.0000000   -1        0.0000000    0
```

```
     31.2899290    -19.7173620  -1      0.0000000  -1      0.0000000   0

0117   1   1
     31.2899290    -19.7173620  -1      0.0000000  -1      0.0000000   0
     31.7199390    -20.1325620  -1      0.0000000  -1      0.0000000   0
     32.1366780    -20.5609680  -1      0.0000000  -1      0.0000000   0

0118   1   1
     32.1366780    -20.5609680  -1      0.0000000  -1      0.0000000   0
     32.5397330    -21.0021790  -1      0.0000000  -1      0.0000000   0
     32.9287130    -21.4557740  -1      0.0000000  -1      0.0000000   0

0119   1   1
     32.9287130    -21.4557740  -1      0.0000000  -1      0.0000000   0
     33.3032360    -21.9213120  -1      0.0000000  -1      0.0000000   0
     33.6629540    -22.3983410  -1      0.0000000  -1      0.0000000   0

0120   1   1
     33.6629540    -22.3983410  -1      0.0000000  -1      0.0000000   0
     34.0075320    -22.8863920  -1      0.0000000  -1      0.0000000   0
     34.3366610    -23.3849790  -1      0.0000000  -1      0.0000000   0

0121   1   1
     34.3366610    -23.3849790  -1      0.0000000  -1      0.0000000   0
     34.6500560    -23.8936100  -1      0.0000000  -1      0.0000000   0
     34.9474520    -24.4117710  -1      0.0000000  -1      0.0000000   0

0122   1   1
     34.9474520    -24.4117710  -1      0.0000000  -1      0.0000000   0
     35.2286050    -24.9389450  -1      0.0000000  -1      0.0000000   0
     35.4933050    -25.4746060  -1      0.0000000  -1      0.0000000   0

0123   1   1
     35.4933050    -25.4746060  -1      0.0000000  -1      0.0000000   0
     35.7413540    -26.0182160  -1      0.0000000  -1      0.0000000   0
     35.9725840    -26.5692330  -1      0.0000000  -1      0.0000000   0

0124   1   1
     35.9725840    -26.5692330  -1      0.0000000  -1      0.0000000   0
     36.1868470    -27.1271100  -1      0.0000000  -1      0.0000000   0
     36.3840200    -27.6912950  -1      0.0000000  -1      0.0000000   0

0125   1   1
     36.3840200    -27.6912950  -1      0.0000000  -1      0.0000000   0
     36.5639950    -28.2612320  -1      0.0000000  -1      0.0000000   0
     36.7266910    -28.8363660  -1      0.0000000  -1      0.0000000   0

0126   1   1
     36.7266910    -28.8363660  -1      0.0000000  -1      0.0000000   0
     36.8720530    -29.4161390  -1      0.0000000  -1      0.0000000   0
     37.0000000    -30.0000000  -1      0.0000000  -1      0.0000000   0

0127   1   4
     37.0000000    -30.0000000  -1      0.0000000  -1      0.0000000   0
     49.5000000    -30.0000000  -1      0.0000000  -1      0.0000000   0
     62.0000000    -30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1

0128   1   4
     62.0000000    -30.0000000  -1      0.0000000  -1      0.0000000  -2   0   1
     92.0000000    -30.0000000  -1      0.0000000  -1      0.0000000   0
    122.0000000    -30.0000000  -1      0.0000000  -1      0.0000000   0
```

```
0129   1   4
    122.0000000   -30.0000000  -1    100.0000000  -1     0.0000000   0
    122.0000000   -15.0000000  -1    100.0000000  -1     0.0000000   0
    122.0000000     0.0000000  -1    100.0000000  -1     0.0000000  -2   0   1

0130   1   4
    122.0000000     0.0000000  -1    100.0000000  -1     0.0000000  -2   0   1
    122.0000000    15.0000000  -1    100.0000000  -1     0.0000000   0
    122.0000000    30.0000000  -1    100.0000000  -1     0.0000000   0

0131   1   4
    122.0000000    30.0000000  -1      0.0000000  -1     0.0000000   0
     92.0000000    30.0000000  -1      0.0000000  -1     0.0000000   0
     62.0000000    30.0000000  -1      0.0000000  -1     0.0000000  -2   0   1

0132   1   4
     62.0000000    30.0000000  -1      0.0000000  -1     0.0000000  -2   0   1
     49.5000000    30.0000000  -1      0.0000000  -1     0.0000000   0
     37.0000000    30.0000000  -1      0.0000000  -1     0.0000000   0

0133   1   2
     37.0000000    30.0000000  -1      0.0000000  -1     0.0000000   0
     36.8720530    29.4161390  -1      0.0000000  -1     0.0000000   0
     36.7266910    28.8363660  -1      0.0000000  -1     0.0000000   0

0134   1   2
     36.7266910    28.8363660  -1      0.0000000  -1     0.0000000   0
     36.5639950    28.2612320  -1      0.0000000  -1     0.0000000   0
     36.3840200    27.6912950  -1      0.0000000  -1     0.0000000   0

0135   1   2
     36.3840200    27.6912950  -1      0.0000000  -1     0.0000000   0
     36.1868470    27.1271100  -1      0.0000000  -1     0.0000000   0
     35.9725840    26.5692330  -1      0.0000000  -1     0.0000000   0

0136   1   2
     35.9725840    26.5692330  -1      0.0000000  -1     0.0000000   0
     35.7413540    26.0182160  -1      0.0000000  -1     0.0000000   0
     35.4933050    25.4746060  -1      0.0000000  -1     0.0000000   0

0137   1   2
     35.4933050    25.4746060  -1      0.0000000  -1     0.0000000   0
     35.2286050    24.9389450  -1      0.0000000  -1     0.0000000   0
     34.9474520    24.4117710  -1      0.0000000  -1     0.0000000   0

0138   1   2
     34.9474520    24.4117710  -1      0.0000000  -1     0.0000000   0
     34.6500560    23.8936100  -1      0.0000000  -1     0.0000000   0
     34.3366610    23.3849790  -1      0.0000000  -1     0.0000000   0

0139   1   2
     34.3366610    23.3849790  -1      0.0000000  -1     0.0000000   0
     34.0075320    22.8863920  -1      0.0000000  -1     0.0000000   0
     33.6629540    22.3983410  -1      0.0000000  -1     0.0000000   0

0140   1   2
     33.6629540    22.3983410  -1      0.0000000  -1     0.0000000   0
     33.3032360    21.9213120  -1      0.0000000  -1     0.0000000   0
     32.9287130    21.4557740  -1      0.0000000  -1     0.0000000   0

0141   1   2
     32.9287130    21.4557740  -1      0.0000000  -1     0.0000000   0
```

```
     32.5397330     21.0021790  -1      0.0000000  -1      0.0000000   0
     32.1366780     20.5609680  -1      0.0000000  -1      0.0000000   0

0142   1   2
     32.1366780     20.5609680  -1      0.0000000  -1      0.0000000   0
     31.7199390     20.1325620  -1      0.0000000  -1      0.0000000   0
     31.2899290     19.7173620  -1      0.0000000  -1      0.0000000   0

0143   1   2
     31.2899290     19.7173620  -1      0.0000000  -1      0.0000000   0
     30.8470810     19.3157570  -1      0.0000000  -1      0.0000000   0
     30.3918430     18.9281140  -1      0.0000000  -1      0.0000000   0

0144   1   2
     30.3918430     18.9281140  -1      0.0000000  -1      0.0000000   0
     29.9246720     18.5547780  -1      0.0000000  -1      0.0000000   0
     29.4460510     18.1960790  -1      0.0000000  -1      0.0000000   0

0145   1   2
     29.4460510     18.1960790  -1      0.0000000  -1      0.0000000   0
     28.9564640     17.8523280  -1      0.0000000  -1      0.0000000   0
     28.4564090     17.5238130  -1      0.0000000  -1      0.0000000   0

0146   1   2
     28.4564090     17.5238130  -1      0.0000000  -1      0.0000000   0
     27.9463980     17.2108080  -1      0.0000000  -1      0.0000000   0
     27.4269430     16.9135610  -1      0.0000000  -1      0.0000000   0

0147   1   2
     27.4269430     16.9135610  -1      0.0000000  -1      0.0000000   0
     26.8985910     16.6322690  -1      0.0000000  -1      0.0000000   0
     26.3618170     16.3672470  -1      0.0000000  -1      0.0000000   0

0148   1   2
     26.3618170     16.3672470  -1      0.0000000  -1      0.0000000   0
     25.8168760     16.1193410  -1      0.0000000  -1      0.0000000   0
     25.2644210     15.8886490  -1      0.0000000  -1      0.0000000   0

0149   1   2
     25.2644210     15.8886490  -1      0.0000000  -1      0.0000000   0
     24.7067210     15.6738580  -1      0.0000000  -1      0.0000000   0
     24.1937660     15.4889750  -1      0.0000000  -1      0.0000000   0

0150   1   2
     24.1937660     15.4889750  -1      0.0000000  -1      0.0000000   0
     23.6814600     15.3152570  -1      0.0000000  -1      0.0000000   0
     23.1680960     15.1513480  -1      0.0000000  -1      0.0000000   0

0151   1   2
     23.1680960     15.1513480  -1      0.0000000  -1      0.0000000   0
     22.6541940     14.9961780  -1      0.0000000  -1      0.0000000   0
     22.1392270     14.8486600  -1      0.0000000  -1      0.0000000   0

0152   1   2
     22.1392270     14.8486600  -1      0.0000000  -1      0.0000000   0
     21.6237560     14.7084000  -1      0.0000000  -1      0.0000000   0
     21.1072320     14.5748160  -1      0.0000000  -1      0.0000000   0

0153   1   2
     21.1072320     14.5748160  -1      0.0000000  -1      0.0000000   0
     20.5900300     14.4476180  -1      0.0000000  -1      0.0000000   0
     20.0719290     14.3264120  -1      0.0000000  -1      0.0000000   0
```

```
0154   1   2
     20.0719290     14.3264120  -1      0.0000000  -1      0.0000000   0
     19.5530890     14.2109080  -1      0.0000000  -1      0.0000000   0
     19.0334590     14.1008050  -1      0.0000000  -1      0.0000000   0

0155   1   2
     19.0334590     14.1008050  -1      0.0000000  -1      0.0000000   0
     18.5130540     13.9958890  -1      0.0000000  -1      0.0000000   0
     17.9918290     13.8959670  -1      0.0000000  -1      0.0000000   0

0156   1   2
     17.9918290     13.8959670  -1      0.0000000  -1      0.0000000   0
     17.4698810     13.8008030  -1      0.0000000  -1      0.0000000   0
     16.9472920     13.7101910  -1      0.0000000  -1      0.0000000   0

0157   1   2
     16.9472920     13.7101910  -1      0.0000000  -1      0.0000000   0
     16.4240060     13.6239530  -1      0.0000000  -1      0.0000000   0
     15.9001150     13.5419440  -1      0.0000000  -1      0.0000000   0

0158   1   2
     15.9001150     13.5419440  -1      0.0000000  -1      0.0000000   0
     15.3755720     13.4640060  -1      0.0000000  -1      0.0000000   0
     14.8504690     13.3900040  -1      0.0000000  -1      0.0000000   0

0159   1   2
     14.8504690     13.3900040  -1      0.0000000  -1      0.0000000   0
     14.3248320     13.3197950  -1      0.0000000  -1      0.0000000   0
     13.7986800     13.2532360  -1      0.0000000  -1      0.0000000   0

0160   1   2
     13.7986800     13.2532360  -1      0.0000000  -1      0.0000000   0
     13.2720240     13.1902110  -1      0.0000000  -1      0.0000000   0
     12.7449000     13.1306100  -1      0.0000000  -1      0.0000000   0

0161   1   2
     12.7449000     13.1306100  -1      0.0000000  -1      0.0000000   0
     12.2173350     13.0743260  -1      0.0000000  -1      0.0000000   0
     11.6893620     13.0212660  -1      0.0000000  -1      0.0000000   0

0162   1   2
     11.6893620     13.0212660  -1      0.0000000  -1      0.0000000   0
     11.1609440     12.9712940  -1      0.0000000  -1      0.0000000   0
     10.6321650     12.9243020  -1      0.0000000  -1      0.0000000   0

0163   1   2
     10.6321650     12.9243020  -1      0.0000000  -1      0.0000000   0
     10.1029990     12.8802070  -1      0.0000000  -1      0.0000000   0
      9.5734790     12.8389350  -1      0.0000000  -1      0.0000000   0

0164   1   2
      9.5734790     12.8389350  -1      0.0000000  -1      0.0000000   0
      9.0435910     12.8003850  -1      0.0000000  -1      0.0000000   0
      8.5133160     12.7644570  -1      0.0000000  -1      0.0000000   0

0165   1   2
      8.5133160     12.7644570  -1      0.0000000  -1      0.0000000   0
      7.9827010     12.7310960  -1      0.0000000  -1      0.0000000   0
      7.4515850     12.7002270  -1      0.0000000  -1      0.0000000   0

0166   1   2
```

```
      7.4515850     12.7002270  -1      0.0000000  -1      0.0000000   0
      6.9200650     12.6717650  -1      0.0000000  -1      0.0000000   0
      6.3876870     12.6455960  -1      0.0000000  -1      0.0000000   0

0167   1   2
      6.3876870     12.6455960  -1      0.0000000  -1      0.0000000   0
      5.8545820     12.6217180  -1      0.0000000  -1      0.0000000   0
      5.3146670     12.5998890  -1      0.0000000  -1      0.0000000   0

0168   1   2
      5.3146670     12.5998890  -1      0.0000000  -1      0.0000000   0
      4.7759650     12.5803830  -1      0.0000000  -1      0.0000000   0
      4.2397240     12.5631460  -1      0.0000000  -1      0.0000000   0

0169   1   2
      4.2397240     12.5631460  -1      0.0000000  -1      0.0000000   0
      3.7053990     12.5481030  -1      0.0000000  -1      0.0000000   0
      3.1729650     12.5352090  -1      0.0000000  -1      0.0000000   0

0170   1   2
      3.1729650     12.5352090  -1      0.0000000  -1      0.0000000   0
      2.6419170     12.5243890  -1      0.0000000  -1      0.0000000   0
      2.1121110     12.5155840  -1      0.0000000  -1      0.0000000   0

0171   1   2
      2.1121110     12.5155840  -1      0.0000000  -1      0.0000000   0
      1.5831520     12.5087610  -1      0.0000000  -1      0.0000000   0
      1.0548970     12.5038980  -1      0.0000000  -1      0.0000000   0

0172   1  16
      1.0548970     12.5038980  -1      0.0000000  -1      0.0000000   0
      0.5269560     12.5009750  -1      0.0000000  -1      0.0000000   0
      0.0000000     12.5000000  -1      0.0000000  -1      0.0000000   1

--------------------------------------------------------------------------------
```

Appendix G:

IGES file of coordinates for Modified Constant-Stress Coupon

The following input file can also be found stored in Objective folder fAV1044714. The name of the file is Al_mod_optimal_3D_msmth_smoothed_002.igs.

```
MSC.Patran generated IGES File from database                            S0000001
/home/username/abaqus/abopt/fillet3dmod/Al_mod_optimal_3D_msmth_iges_002S0000002
.d                                                                      S0000003
,,22HMSC.Patran IGES Access,80H/home/username/abaqus/abopt/fillet3dmod/AG0000001
l_mod_optimal_3D_msmth_smoothed_002.igs,35HMSC.Patran 19.0.132332 MSC.SoG0000002
ftware,11H19.0.132332,                                                  G0000003
32,38,6,,,22HMSC.Patran IGES Export,                                    G0000004
1.0, 2,2HMM,1,0,13H140501.142551,0.200000E-04,37.,                      G0000005
8Husername,23HMSC.Patran User's Group,                                  G0000006
11,0,13H140501.142551,;                                                 G0000007
     116       1       2       2       0       0       0        000000000D0000001
     116       0       0       1       0       0       0POINT           1D0000002
     116       2       2       2       0       0       0        000000000D0000003
     116       0       0       1       0       0       0POINT           2D0000004
     116       3       2       2       0       0       0        000000000D0000005
     116       0       0       1       0       0       0POINT           3D0000006
     116       4       2       2       0       0       0        000000000D0000007
     116       0       0       1       0       0       0POINT           4D0000008
     116       5       2       2       0       0       0        000000000D0000009
     116       0       0       1       0       0       0POINT           5D0000010
     116       6       2       2       0       0       0        000000000D0000011
     116       0       0       1       0       0       0POINT           6D0000012
     116       7       2       2       0       0       0        000000000D0000013
     116       0       0       1       0       0       0POINT           7D0000014
     116       8       2       2       0       0       0        000000000D0000015
     116       0       0       1       0       0       0POINT           8D0000016
     116       9       2       2       0       0       0        000000000D0000017
     116       0       0       1       0       0       0POINT           9D0000018
     116      10       2       2       0       0       0        000000000D0000019
     116       0       0       1       0       0       0POINT          10D0000020
     116      11       2       2       0       0       0        000000000D0000021
     116       0       0       1       0       0       0POINT          11D0000022
     116      12       2       2       0       0       0        000000000D0000023
     116       0       0       1       0       0       0POINT          12D0000024
     116      13       2       2       0       0       0        000000000D0000025
     116       0       0       1       0       0       0POINT          13D0000026
     116      14       2       2       0       0       0        000000000D0000027
     116       0       0       1       0       0       0POINT          14D0000028
     116      15       2       2       0       0       0        000000000D0000029
     116       0       0       1       0       0       0POINT          15D0000030
     116      16       2       2       0       0       0        000000000D0000031
     116       0       0       1       0       0       0POINT          16D0000032
     116      17       2       2       0       0       0        000000000D0000033
     116       0       0       1       0       0       0POINT          17D0000034
     116      18       2       2       0       0       0        000000000D0000035
     116       0       0       1       0       0       0POINT          18D0000036
     116      19       2       2       0       0       0        000000000D0000037
```

116	0	0	1	0	0	0POINT	19D0000038
116	20	2	2	0	0	0	000000000D0000039
116	0	0	1	0	0	0POINT	20D0000040
116	21	2	2	0	0	0	000000000D0000041
116	0	0	1	0	0	0POINT	21D0000042
116	22	2	2	0	0	0	000000000D0000043
116	0	0	1	0	0	0POINT	22D0000044
116	23	2	2	0	0	0	000000000D0000045
116	0	0	1	0	0	0POINT	23D0000046
116	24	2	2	0	0	0	000000000D0000047
116	0	0	1	0	0	0POINT	24D0000048
116	25	2	2	0	0	0	000000000D0000049
116	0	0	1	0	0	0POINT	25D0000050
116	26	2	2	0	0	0	000000000D0000051
116	0	0	1	0	0	0POINT	26D0000052
116	27	2	2	0	0	0	000000000D0000053
116	0	0	1	0	0	0POINT	27D0000054
116	28	2	2	0	0	0	000000000D0000055
116	0	0	1	0	0	0POINT	28D0000056
116	29	2	2	0	0	0	000000000D0000057
116	0	0	1	0	0	0POINT	29D0000058
116	30	2	2	0	0	0	000000000D0000059
116	0	0	1	0	0	0POINT	30D0000060
116	31	2	2	0	0	0	000000000D0000061
116	0	0	1	0	0	0POINT	31D0000062
116	32	2	2	0	0	0	000000000D0000063
116	0	0	1	0	0	0POINT	32D0000064
116	33	2	2	0	0	0	000000000D0000065
116	0	0	1	0	0	0POINT	33D0000066
116	34	2	2	0	0	0	000000000D0000067
116	0	0	1	0	0	0POINT	34D0000068
116	35	2	2	0	0	0	000000000D0000069
116	0	0	1	0	0	0POINT	35D0000070
116	36	2	2	0	0	0	000000000D0000071
116	0	0	1	0	0	0POINT	36D0000072
116	37	2	2	0	0	0	000000000D0000073
116	0	0	1	0	0	0POINT	37D0000074
116	38	2	2	0	0	0	000000000D0000075
116	0	0	1	0	0	0POINT	38D0000076
116	39	2	2	0	0	0	000000000D0000077
116	0	0	1	0	0	0POINT	39D0000078
116	40	2	2	0	0	0	000000000D0000079
116	0	0	1	0	0	0POINT	40D0000080
116	41	2	2	0	0	0	000000000D0000081
116	0	0	1	0	0	0POINT	41D0000082
116	42	2	2	0	0	0	000000000D0000083
116	0	0	1	0	0	0POINT	42D0000084
116	43	2	2	0	0	0	000000000D0000085
116	0	0	1	0	0	0POINT	43D0000086
116	44	2	2	0	0	0	000000000D0000087
116	0	0	1	0	0	0POINT	44D0000088
116	45	2	2	0	0	0	000000000D0000089
116	0	0	1	0	0	0POINT	45D0000090
116	46	2	2	0	0	0	000000000D0000091
116	0	0	1	0	0	0POINT	46D0000092
116	47	2	2	0	0	0	000000000D0000093
116	0	0	1	0	0	0POINT	47D0000094
116	48	2	2	0	0	0	000000000D0000095
116	0	0	1	0	0	0POINT	48D0000096
116	49	2	2	0	0	0	000000000D0000097

```
     116       0       0       1       0       0       0POINT        49D0000098
     116      50       2       2       0       0       0       000000000D0000099
     116       0       0       1       0       0       0POINT        50D0000100
     116      51       2       2       0       0       0       000000000D0000101
     116       0       0       1       0       0       0POINT        51D0000102
     116      52       2       2       0       0       0       000000000D0000103
     116       0       0       1       0       0       0POINT        52D0000104
     116      53       2       2       0       0       0       000000000D0000105
     116       0       0       1       0       0       0POINT        53D0000106
     116      54       2       2       0       0       0       000000000D0000107
     116       0       0       1       0       0       0POINT        54D0000108
     116      55       2       2       0       0       0       000000000D0000109
     116       0       0       1       0       0       0POINT        55D0000110
     116      56       2       2       0       0       0       000000000D0000111
     116       0       0       1       0       0       0POINT        56D0000112
     116      57       2       2       0       0       0       000000000D0000113
     116       0       0       1       0       0       0POINT        57D0000114
     116      58       2       2       0       0       0       000000000D0000115
     116       0       0       1       0       0       0POINT        58D0000116
     116      59       2       2       0       0       0       000000000D0000117
     116       0       0       1       0       0       0POINT        59D0000118
     116      60       2       2       0       0       0       000000000D0000119
     116       0       0       1       0       0       0POINT        60D0000120
     116      61       2       2       0       0       0       000000000D0000121
     116       0       0       1       0       0       0POINT        61D0000122
     116      62       2       2       0       0       0       000000000D0000123
     116       0       0       1       0       0       0POINT        62D0000124
     116      63       2       2       0       0       0       000000000D0000125
     116       0       0       1       0       0       0POINT        63D0000126
     116      64       2       2       0       0       0       000000000D0000127
     116       0       0       1       0       0       0POINT        64D0000128
     116      65       2       2       0       0       0       000000000D0000129
     116       0       0       1       0       0       0POINT        65D0000130
     116      66       2       2       0       0       0       000000000D0000131
     116       0       0       1       0       0       0POINT        66D0000132
     116      67       2       2       0       0       0       000000000D0000133
     116       0       0       1       0       0       0POINT        67D0000134
     116      68       2       2       0       0       0       000000000D0000135
     116       0       0       1       0       0       0POINT        68D0000136
     116      69       2       2       0       0       0       000000000D0000137
     116       0       0       1       0       0       0POINT        69D0000138
     116      70       2       2       0       0       0       000000000D0000139
     116       0       0       1       0       0       0POINT        70D0000140
     116      71       2       2       0       0       0       000000000D0000141
     116       0       0       1       0       0       0POINT        71D0000142
     116      72       2       2       0       0       0       000000000D0000143
     116       0       0       1       0       0       0POINT        72D0000144
     116      73       2       2       0       0       0       000000000D0000145
     116       0       0       1       0       0       0POINT        73D0000146
     116      74       2       2       0       0       0       000000000D0000147
     116       0       0       1       0       0       0POINT        74D0000148
     116      75       2       2       0       0       0       000000000D0000149
     116       0       0       1       0       0       0POINT        75D0000150
     116      76       2       2       0       0       0       000000000D0000151
     116       0       0       1       0       0       0POINT        76D0000152
     116      77       2       2       0       0       0       000000000D0000153
     116       0       0       1       0       0       0POINT        77D0000154
     116      78       2       2       0       0       0       000000000D0000155
     116       0       0       1       0       0       0POINT        78D0000156
     116      79       2       2       0       0       0       000000000D0000157
```

```
     116       0       0       1       0       0       0POINT         79D0000158
     116      80       2       2       0       0       0       000000000D0000159
     116       0       0       1       0       0       0POINT         80D0000160
     116      81       2       2       0       0       0       000000000D0000161
     116       0       0       1       0       0       0POINT         81D0000162
     116      82       2       2       0       0       0       000000000D0000163
     116       0       0       1       0       0       0POINT         82D0000164
     116      83       2       2       0       0       0       000000000D0000165
     116       0       0       1       0       0       0POINT         83D0000166
     116      84       2       2       0       0       0       000000000D0000167
     116       0       0       1       0       0       0POINT         84D0000168
     116      85       2       2       0       0       0       000000000D0000169
     116       0       0       1       0       0       0POINT         85D0000170
     116      86       2       2       0       0       0       000000000D0000171
     116       0       0       1       0       0       0POINT         86D0000172
     116      87       2       2       0       0       0       000000000D0000173
     116       0       0       1       0       0       0POINT         87D0000174
     116      88       2       2       0       0       0       000000000D0000175
     116       0       0       1       0       0       0POINT         88D0000176
     116      89       2       2       0       0       0       000000000D0000177
     116       0       0       1       0       0       0POINT         89D0000178
     116      90       2       2       0       0       0       000000000D0000179
     116       0       0       1       0       0       0POINT         90D0000180
     116      91       2       2       0       0       0       000000000D0000181
     116       0       0       1       0       0       0POINT         91D0000182
     116      92       2       2       0       0       0       000000000D0000183
     116       0       0       1       0       0       0POINT         92D0000184
     116      93       2       2       0       0       0       000000000D0000185
     116       0       0       1       0       0       0POINT         93D0000186
     116      94       2       2       0       0       0       000000000D0000187
     116       0       0       1       0       0       0POINT         94D0000188
     116      95       2       2       0       0       0       000000000D0000189
     116       0       0       1       0       0       0POINT         95D0000190
     116      96       2       2       0       0       0       000000000D0000191
     116       0       0       1       0       0       0POINT         96D0000192
     116      97       2       2       0       0       0       000000000D0000193
     116       0       0       1       0       0       0POINT         97D0000194
     116      98       2       2       0       0       0       000000000D0000195
     116       0       0       1       0       0       0POINT         98D0000196
     116      99       2       2       0       0       0       000000000D0000197
     116       0       0       1       0       0       0POINT         99D0000198
     116     100       2       2       0       0       0       000000000D0000199
     116       0       0       1       0       0       0POINT        100D0000200
     116     101       2       2       0       0       0       000000000D0000201
     116       0       0       1       0       0       0POINT        101D0000202
     116     102       2       2       0       0       0       000000000D0000203
     116       0       0       1       0       0       0POINT        102D0000204
     116     103       2       2       0       0       0       000000000D0000205
     116       0       0       1       0       0       0POINT        103D0000206
     116     104       2       2       0       0       0       000000000D0000207
     116       0       0       1       0       0       0POINT        104D0000208
     116     105       2       2       0       0       0       000000000D0000209
     116       0       0       1       0       0       0POINT        105D0000210
     116     106       2       2       0       0       0       000000000D0000211
     116       0       0       1       0       0       0POINT        106D0000212
     116     107       2       2       0       0       0       000000000D0000213
     116       0       0       1       0       0       0POINT        107D0000214
     116     108       2       2       0       0       0       000000000D0000215
     116       0       0       1       0       0       0POINT        108D0000216
     116     109       2       2       0       0       0       000000000D0000217
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     116       0       0       1       0       0       0POINT       109D0000218
     116     110       2       2       0       0       0     000000000D0000219
     116       0       0       1       0       0       0POINT       110D0000220
     116     111       2       2       0       0       0     000000000D0000221
     116       0       0       1       0       0       0POINT       111D0000222
     116     112       2       2       0       0       0     000000000D0000223
     116       0       0       1       0       0       0POINT       112D0000224
     116     113       2       2       0       0       0     000000000D0000225
     116       0       0       1       0       0       0POINT       113D0000226
     116     114       2       2       0       0       0     000000000D0000227
     116       0       0       1       0       0       0POINT       114D0000228
     116     115       2       2       0       0       0     000000000D0000229
     116       0       0       1       0       0       0POINT       115D0000230
     116     116       2       2       0       0       0     000000000D0000231
     116       0       0       1       0       0       0POINT       116D0000232
     116     117       2       2       0       0       0     000000000D0000233
     116       0       0       1       0       0       0POINT       117D0000234
     116     118       2       2       0       0       0     000000000D0000235
     116       0       0       1       0       0       0POINT       118D0000236
     116     119       2       2       0       0       0     000000000D0000237
     116       0       0       1       0       0       0POINT       119D0000238
     116     120       2       2       0       0       0     000000000D0000239
     116       0       0       1       0       0       0POINT       120D0000240
     116     121       2       2       0       0       0     000000000D0000241
     116       0       0       1       0       0       0POINT       121D0000242
     116     122       2       2       0       0       0     000000000D0000243
     116       0       0       1       0       0       0POINT       122D0000244
     116     123       2       2       0       0       0     000000000D0000245
     116       0       0       1       0       0       0POINT       123D0000246
     116     124       2       2       0       0       0     000000000D0000247
     116       0       0       1       0       0       0POINT       124D0000248
     116     125       2       2       0       0       0     000000000D0000249
     116       0       0       1       0       0       0POINT       125D0000250
     116     126       2       2       0       0       0     000000000D0000251
     116       0       0       1       0       0       0POINT       126D0000252
     116     127       2       2       0       0       0     000000000D0000253
     116       0       0       1       0       0       0POINT       127D0000254
     116     128       2       2       0       0       0     000000000D0000255
     116       0       0       1       0       0       0POINT       128D0000256
     116     129       2       2       0       0       0     000000000D0000257
     116       0       0       1       0       0       0POINT       129D0000258
     116     130       2       2       0       0       0     000000000D0000259
     116       0       0       1       0       0       0POINT       130D0000260
     116     131       2       2       0       0       0     000000000D0000261
     116       0       0       1       0       0       0POINT       131D0000262
     116     132       2       2       0       0       0     000000000D0000263
     116       0       0       1       0       0       0POINT       132D0000264
     116     133       2       2       0       0       0     000000000D0000265
     116       0       0       1       0       0       0POINT       133D0000266
     116     134       2       2       0       0       0     000000000D0000267
     116       0       0       1       0       0       0POINT       134D0000268
     116     135       2       2       0       0       0     000000000D0000269
     116       0       0       1       0       0       0POINT       135D0000270
     116     136       2       2       0       0       0     000000000D0000271
     116       0       0       1       0       0       0POINT       136D0000272
     116     137       2       2       0       0       0     000000000D0000273
     116       0       0       1       0       0       0POINT       137D0000274
     116     138       2       2       0       0       0     000000000D0000275
     116       0       0       1       0       0       0POINT       138D0000276
     116     139       2       2       0       0       0     000000000D0000277
```

116	0	0	1	0	0	0POINT	139D0000278
116	140	2	2	0	0	0	000000000D0000279
116	0	0	1	0	0	0POINT	140D0000280
116	141	2	2	0	0	0	000000000D0000281
116	0	0	1	0	0	0POINT	141D0000282
116	142	2	2	0	0	0	000000000D0000283
116	0	0	1	0	0	0POINT	142D0000284
116	143	2	2	0	0	0	000000000D0000285
116	0	0	1	0	0	0POINT	143D0000286
116	144	2	2	0	0	0	000000000D0000287
116	0	0	1	0	0	0POINT	144D0000288
116	145	2	2	0	0	0	000000000D0000289
116	0	0	1	0	0	0POINT	145D0000290
116	146	2	2	0	0	0	000000000D0000291
116	0	0	1	0	0	0POINT	146D0000292
116	147	2	2	0	0	0	000000000D0000293
116	0	0	1	0	0	0POINT	147D0000294
116	148	2	2	0	0	0	000000000D0000295
116	0	0	1	0	0	0POINT	148D0000296
116	149	2	2	0	0	0	000000000D0000297
116	0	0	1	0	0	0POINT	149D0000298
116	150	2	2	0	0	0	000000000D0000299
116	0	0	1	0	0	0POINT	150D0000300
116	151	2	2	0	0	0	000000000D0000301
116	0	0	1	0	0	0POINT	151D0000302
116	152	2	2	0	0	0	000000000D0000303
116	0	0	1	0	0	0POINT	152D0000304
116	153	2	2	0	0	0	000000000D0000305
116	0	0	1	0	0	0POINT	153D0000306
116	154	2	2	0	0	0	000000000D0000307
116	0	0	1	0	0	0POINT	154D0000308
116	155	2	2	0	0	0	000000000D0000309
116	0	0	1	0	0	0POINT	155D0000310
116	156	2	2	0	0	0	000000000D0000311
116	0	0	1	0	0	0POINT	156D0000312
116	157	2	2	0	0	0	000000000D0000313
116	0	0	1	0	0	0POINT	157D0000314
116	158	2	2	0	0	0	000000000D0000315
116	0	0	1	0	0	0POINT	158D0000316
116	159	2	2	0	0	0	000000000D0000317
116	0	0	1	0	0	0POINT	159D0000318
116	160	2	2	0	0	0	000000000D0000319
116	0	0	1	0	0	0POINT	160D0000320
116	161	2	2	0	0	0	000000000D0000321
116	0	0	1	0	0	0POINT	161D0000322
124	162	2	1	0	0	0	000010000D0000323
124	0	0	4	0	0	0MATRIX	1D0000324
100	166	2	1	0	0	323	000000000D0000325
100	0	0	3	0	0	0CIRC ARC	1D0000326
124	169	2	1	0	0	0	000010000D0000327
124	0	0	4	0	0	0MATRIX	2D0000328
100	173	2	1	0	0	327	000000000D0000329
100	0	0	3	0	0	0CIRC ARC	2D0000330
124	176	2	1	0	0	0	000010000D0000331
124	0	0	4	0	0	0MATRIX	3D0000332
100	180	2	1	0	0	331	000000000D0000333
100	0	0	3	0	0	0CIRC ARC	3D0000334
124	183	2	1	0	0	0	000010000D0000335
124	0	0	4	0	0	0MATRIX	4D0000336
100	187	2	1	0	0	335	000000000D0000337

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100       0       0       3       0       0       0CIRC ARC        4D0000338
124     190       2       1       0       0       0        000010000D0000339
124       0       0       4       0       0       0MATRIX          5D0000340
100     194       2       1       0       0     339        000000000D0000341
100       0       0       3       0       0       0CIRC ARC        5D0000342
124     197       2       1       0       0       0        000010000D0000343
124       0       0       4       0       0       0MATRIX          6D0000344
100     201       2       1       0       0     343        000000000D0000345
100       0       0       3       0       0       0CIRC ARC        6D0000346
124     204       2       1       0       0       0        000010000D0000347
124       0       0       4       0       0       0MATRIX          7D0000348
100     208       2       1       0       0     347        000000000D0000349
100       0       0       3       0       0       0CIRC ARC        7D0000350
124     211       2       1       0       0       0        000010000D0000351
124       0       0       4       0       0       0MATRIX          8D0000352
100     215       2       1       0       0     351        000000000D0000353
100       0       0       3       0       0       0CIRC ARC        8D0000354
124     218       2       1       0       0       0        000010000D0000355
124       0       0       4       0       0       0MATRIX          9D0000356
100     222       2       1       0       0     355        000000000D0000357
100       0       0       3       0       0       0CIRC ARC        9D0000358
124     225       2       1       0       0       0        000010000D0000359
124       0       0       4       0       0       0MATRIX         10D0000360
100     229       2       1       0       0     359        000000000D0000361
100       0       0       3       0       0       0CIRC ARC       10D0000362
124     232       2       1       0       0       0        000010000D0000363
124       0       0       4       0       0       0MATRIX         11D0000364
100     236       2       1       0       0     363        000000000D0000365
100       0       0       3       0       0       0CIRC ARC       11D0000366
124     239       2       1       0       0       0        000010000D0000367
124       0       0       4       0       0       0MATRIX         12D0000368
100     243       2       1       0       0     367        000000000D0000369
100       0       0       3       0       0       0CIRC ARC       12D0000370
124     246       2       1       0       0       0        000010000D0000371
124       0       0       4       0       0       0MATRIX         13D0000372
100     250       2       1       0       0     371        000000000D0000373
100       0       0       3       0       0       0CIRC ARC       13D0000374
124     253       2       1       0       0       0        000010000D0000375
124       0       0       4       0       0       0MATRIX         14D0000376
100     257       2       1       0       0     375        000000000D0000377
100       0       0       3       0       0       0CIRC ARC       14D0000378
124     260       2       1       0       0       0        000010000D0000379
124       0       0       4       0       0       0MATRIX         15D0000380
100     264       2       1       0       0     379        000000000D0000381
100       0       0       3       0       0       0CIRC ARC       15D0000382
124     267       2       1       0       0       0        000010000D0000383
124       0       0       4       0       0       0MATRIX         16D0000384
100     271       2       1       0       0     383        000000000D0000385
100       0       0       3       0       0       0CIRC ARC       16D0000386
124     274       2       1       0       0       0        000010000D0000387
124       0       0       4       0       0       0MATRIX         17D0000388
100     278       2       1       0       0     387        000000000D0000389
100       0       0       3       0       0       0CIRC ARC       17D0000390
124     281       2       1       0       0       0        000010000D0000391
124       0       0       4       0       0       0MATRIX         18D0000392
100     285       2       1       0       0     391        000000000D0000393
100       0       0       3       0       0       0CIRC ARC       18D0000394
124     288       2       1       0       0       0        000010000D0000395
124       0       0       4       0       0       0MATRIX         19D0000396
100     292       2       1       0       0     395        000000000D0000397
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     100       0       0       3       0       0       0CIRC ARC      19D0000398
     124     295       2       1       0       0       0       000010000D0000399
     124       0       0       4       0       0       0MATRIX        20D0000400
     100     299       2       1       0       0     399       000000000D0000401
     100       0       0       3       0       0       0CIRC ARC      20D0000402
     124     302       2       1       0       0       0       000010000D0000403
     124       0       0       4       0       0       0MATRIX        21D0000404
     100     306       2       1       0       0     403       000000000D0000405
     100       0       0       3       0       0       0CIRC ARC      21D0000406
     124     309       2       1       0       0       0       000010000D0000407
     124       0       0       4       0       0       0MATRIX        22D0000408
     100     313       2       1       0       0     407       000000000D0000409
     100       0       0       3       0       0       0CIRC ARC      22D0000410
     124     316       2       1       0       0       0       000010000D0000411
     124       0       0       4       0       0       0MATRIX        23D0000412
     100     320       2       1       0       0     411       000000000D0000413
     100       0       0       3       0       0       0CIRC ARC      23D0000414
     124     323       2       1       0       0       0       000010000D0000415
     124       0       0       4       0       0       0MATRIX        24D0000416
     100     327       2       1       0       0     415       000000000D0000417
     100       0       0       3       0       0       0CIRC ARC      24D0000418
     124     330       2       1       0       0       0       000010000D0000419
     124       0       0       4       0       0       0MATRIX        25D0000420
     100     334       2       1       0       0     419       000000000D0000421
     100       0       0       3       0       0       0CIRC ARC      25D0000422
     124     337       2       1       0       0       0       000010000D0000423
     124       0       0       4       0       0       0MATRIX        26D0000424
     100     341       2       1       0       0     423       000000000D0000425
     100       0       0       3       0       0       0CIRC ARC      26D0000426
     124     344       2       1       0       0       0       000010000D0000427
     124       0       0       4       0       0       0MATRIX        27D0000428
     100     348       2       1       0       0     427       000000000D0000429
     100       0       0       3       0       0       0CIRC ARC      27D0000430
     124     351       2       1       0       0       0       000010000D0000431
     124       0       0       4       0       0       0MATRIX        28D0000432
     100     355       2       1       0       0     431       000000000D0000433
     100       0       0       3       0       0       0CIRC ARC      28D0000434
     124     358       2       1       0       0       0       000010000D0000435
     124       0       0       4       0       0       0MATRIX        29D0000436
     100     362       2       1       0       0     435       000000000D0000437
     100       0       0       3       0       0       0CIRC ARC      29D0000438
     124     365       2       1       0       0       0       000010000D0000439
     124       0       0       4       0       0       0MATRIX        30D0000440
     100     369       2       1       0       0     439       000000000D0000441
     100       0       0       3       0       0       0CIRC ARC      30D0000442
     124     372       2       1       0       0       0       000010000D0000443
     124       0       0       4       0       0       0MATRIX        31D0000444
     100     376       2       1       0       0     443       000000000D0000445
     100       0       0       3       0       0       0CIRC ARC      31D0000446
     124     379       2       1       0       0       0       000010000D0000447
     124       0       0       4       0       0       0MATRIX        32D0000448
     100     383       2       1       0       0     447       000000000D0000449
     100       0       0       3       0       0       0CIRC ARC      32D0000450
     124     386       2       1       0       0       0       000010000D0000451
     124       0       0       4       0       0       0MATRIX        33D0000452
     100     390       2       1       0       0     451       000000000D0000453
     100       0       0       3       0       0       0CIRC ARC      33D0000454
     124     393       2       1       0       0       0       000010000D0000455
     124       0       0       4       0       0       0MATRIX        34D0000456
     100     397       2       1       0       0     455       000000000D0000457
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 100       0       0       3       0       0      0CIRC ARC       34D0000458
 124     400       2       1       0       0      0        000010000D0000459
 124       0       0       4       0       0      0MATRIX         35D0000460
 100     404       2       1       0       0    459        000000000D0000461
 100       0       0       3       0       0      0CIRC ARC       35D0000462
 124     407       2       1       0       0      0        000010000D0000463
 124       0       0       4       0       0      0MATRIX         36D0000464
 100     411       2       1       0       0    463        000000000D0000465
 100       0       0       3       0       0      0CIRC ARC       36D0000466
 124     414       2       1       0       0      0        000010000D0000467
 124       0       0       4       0       0      0MATRIX         37D0000468
 100     418       2       1       0       0    467        000000000D0000469
 100       0       0       3       0       0      0CIRC ARC       37D0000470
 124     421       2       1       0       0      0        000010000D0000471
 124       0       0       4       0       0      0MATRIX         38D0000472
 100     425       2       1       0       0    471        000000000D0000473
 100       0       0       3       0       0      0CIRC ARC       38D0000474
 124     428       2       1       0       0      0        000010000D0000475
 124       0       0       4       0       0      0MATRIX         39D0000476
 100     432       2       1       0       0    475        000000000D0000477
 100       0       0       3       0       0      0CIRC ARC       39D0000478
 124     435       2       1       0       0      0        000010000D0000479
 124       0       0       4       0       0      0MATRIX         40D0000480
 100     439       2       1       0       0    479        000000000D0000481
 100       0       0       3       0       0      0CIRC ARC       40D0000482
 124     442       2       1       0       0      0        000010000D0000483
 124       0       0       4       0       0      0MATRIX         41D0000484
 100     446       2       1       0       0    483        000000000D0000485
 100       0       0       3       0       0      0CIRC ARC       41D0000486
 124     449       2       1       0       0      0        000010000D0000487
 124       0       0       4       0       0      0MATRIX         42D0000488
 100     453       2       1       0       0    487        000000000D0000489
 100       0       0       3       0       0      0CIRC ARC       42D0000490
 124     456       2       1       0       0      0        000010000D0000491
 124       0       0       4       0       0      0MATRIX         43D0000492
 100     460       2       1       0       0    491        000000000D0000493
 100       0       0       3       0       0      0CIRC ARC       43D0000494
 124     463       2       1       0       0      0        000010000D0000495
 124       0       0       4       0       0      0MATRIX         44D0000496
 100     467       2       1       0       0    495        000000000D0000497
 100       0       0       3       0       0      0CIRC ARC       44D0000498
 124     470       2       1       0       0      0        000010000D0000499
 124       0       0       4       0       0      0MATRIX         45D0000500
 100     474       2       1       0       0    499        000000000D0000501
 100       0       0       3       0       0      0CIRC ARC       45D0000502
 124     477       2       1       0       0      0        000010000D0000503
 124       0       0       4       0       0      0MATRIX         46D0000504
 100     481       2       1       0       0    503        000000000D0000505
 100       0       0       3       0       0      0CIRC ARC       46D0000506
 124     484       2       1       0       0      0        000010000D0000507
 124       0       0       4       0       0      0MATRIX         47D0000508
 100     488       2       1       0       0    507        000000000D0000509
 100       0       0       3       0       0      0CIRC ARC       47D0000510
 124     491       2       1       0       0      0        000010000D0000511
 124       0       0       4       0       0      0MATRIX         48D0000512
 100     495       2       1       0       0    511        000000000D0000513
 100       0       0       3       0       0      0CIRC ARC       48D0000514
 124     498       2       1       0       0      0        000010000D0000515
 124       0       0       4       0       0      0MATRIX         49D0000516
 100     502       2       1       0       0    515        000000000D0000517
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     100       0       0       3       0       0       0CIRC ARC      49D0000518
     124     505       2       1       0       0       0       000010000D0000519
     124       0       0       4       0       0       0MATRIX        50D0000520
     100     509       2       1       0       0     519       000000000D0000521
     100       0       0       3       0       0       0CIRC ARC      50D0000522
     124     512       2       1       0       0       0       000010000D0000523
     124       0       0       4       0       0       0MATRIX        51D0000524
     100     516       2       1       0       0     523       000000000D0000525
     100       0       0       3       0       0       0CIRC ARC      51D0000526
     124     519       2       1       0       0       0       000010000D0000527
     124       0       0       4       0       0       0MATRIX        52D0000528
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     100    1118       2       1       0       0     867       000000000D0000869
     100       0       0       3       0       0       0CIRC ARC     137D0000870
     124    1121       2       1       0       0       0       000010000D0000871
     124       0       0       4       0       0       0MATRIX       138D0000872
     100    1125       2       1       0       0     871       000000000D0000873
     100       0       0       3       0       0       0CIRC ARC     138D0000874
     124    1128       2       1       0       0       0       000010000D0000875
     124       0       0       4       0       0       0MATRIX       139D0000876
     100    1132       2       1       0       0     875       000000000D0000877
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     124       0       0       4       0       0       0MATRIX        140D0000880
     100    1139       2       1       0       0     879       000000000D0000881
     100       0       0       3       0       0       0CIRC ARC      140D0000882
     124    1142       2       1       0       0       0       000010000D0000883
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     100    1146       2       1       0       0     883       000000000D0000885
     100       0       0       3       0       0       0CIRC ARC      141D0000886
     124    1149       2       1       0       0       0       000010000D0000887
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     124    1156       2       1       0       0       0       000010000D0000891
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     100    1160       2       1       0       0     891       000000000D0000893
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     124    1163       2       1       0       0       0       000010000D0000895
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     100    1167       2       1       0       0     895       000000000D0000897
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     124    1170       2       1       0       0       0       000010000D0000899
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     100    1174       2       1       0       0     899       000000000D0000901
     100       0       0       3       0       0       0CIRC ARC      145D0000902
     124    1177       2       1       0       0       0       000010000D0000903
     124       0       0       4       0       0       0MATRIX        146D0000904
     100    1181       2       1       0       0     903       000000000D0000905
     100       0       0       3       0       0       0CIRC ARC      146D0000906
     124    1184       2       1       0       0       0       000010000D0000907
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     100    1188       2       1       0       0     907       000000000D0000909
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     124    1191       2       1       0       0       0       000010000D0000911
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     100    1195       2       1       0       0     911       000000000D0000913
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     100    1251       2       1       0       0     943        000000000D0000945
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     124    1254       2       1       0       0       0        000010000D0000947
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     124    1275       2       1       0       0       0        000010000D0000959
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19. ABSTRACT

This report details the development of a modified constant-stress coupon for use in fatigue testing. This novel coupon design has a significantly greater surface area along the notch boundary that is subjected to the peak stress, and it is useful in studies of the probabilistic growth of in-service fatigue cracks where fatigue life is governed by the most severe defect. The extended region of uniform stress is achieved by shape optimisation of the notch boundary, resulting in the elimination of the highly-localised stress concentration that is a characteristic feature of a traditional dog-bone coupon. The presence of an extensive region of uniform stress increases the incidence of fatigue cracking from small naturally-occurring surface imperfections or discontinuities, as well as more uniformly distributing the fatigue cracking over the region of constant stress. Stress intensity factors have also been computed for simulated crack growth trajectories for edge cracks starting at various locations distributed along the notch boundary. Use of the constant-stress coupon reduces the number of coupons that need to be tested in order to attain desired statistical confidence levels, leading to significant time savings and greatly reduced costs in conducting fatigue testing programs studying the initiation and growth behaviour of small cracks.